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Enhancing seismic design in high-hazard zones: Code gaps and recommended revisions

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Abstract

Current seismic design codes adopt a life-safety philosophy based on probabilistic seismic hazard models with return periods of 50–100 years. This approach accepts significant structural and nonstructural damage under major earthquakes, relying heavily on high ductility demands and seismic force reduction factors (R-factors). However, recent earthquake events in high-seismicity regions—particularly Turkey—reveal the inadequacy of these assumptions, as many newly constructed buildings have suffered severe damage or collapse within less than five years of service. Additionally, nonstructural elements such as brittle brick partition walls continue to cause life-threatening hazards despite structural stability. This paper examines critical gaps in existing seismic codes related to (1) the use of brittle partition walls, (2) insufficient structural damping requirements for high-occupancy buildings, and (3) over-reliance on large R-factors that significantly reduce design base shear. Based on observed earthquake performance, field reconnaissance, and analytical understanding of structural dynamics, the paper proposes three new code provisions: (a) restriction of brittle masonry partitions in high-seismic zones, (b) mandatory supplemental damping of at least 15% of critical damping in buildings with high occupancy, and (c) reduction of R-factors to improve structural integrity and post-earthquake functionality. These revisions aim to shift the seismic design philosophy toward resilience, continuity of function, and long-term safety.

Keywords: Seismic Design Philosophy; Ductility; Damping; Partition Walls; R-Factor; Earthquake Engineering; High-Seismicity Regions; Structural Resilience

1. Introduction

Despite five decades of advancements, many high-seismicity regions continue to face catastrophic losses during earthquakes, largely because conventional seismic codes are built on limiting assumptions: that major events are rare, single occurrences within a building's life; that moderate to severe structural damage is permissible provided life safety is protected; and that nonstructural components need not meet strict ductility standards. This approach prioritizes minimizing initial construction cost while accepting significant post-earthquake damage. However, recent seismic events, such as the sequence of major earthquakes (Mw > 6.5) in Turkey occurring at short intervals of 4–7 years, critically challenge these assumptions. Observations of severe structural and nonstructural damage in newly constructed residential and critical facilities indicate that current code provisions may not adequately account for the increasing frequency of damaging earthquakes or the demands of modern urban occupancy. Notably, nonstructural elements have emerged as a major contributor to loss, as brittle hollow brick partition walls frequently collapse under moderate shaking, creating significant debris, falling hazards, and obstructing evacuation paths, often leading to injuries that far exceed fatalities, as seen in the paper published by Haryanto et al [1]. Furthermore, the absence of minimum

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damping requirements leaves buildings susceptible to resonance, while the reliability of widely used Response Modification Factors (R-factors) is questionable given evolving seismicity and construction variability. This paper argues that seismic design must evolve beyond the collapse-prevention paradigm to address these critical shortcomings, specifically focusing on reducing non-fatal casualties and enabling post-event functionality. To achieve this, three targeted revisions are proposed for seismic codes: mandating ductile alternatives for brittle partition walls, establishing a minimum structural damping threshold, and reducing the R-factors to improve structural robustness, thereby enhancing life safety, resilience, functionality, and mitigating long-term structural cost loss[2].

2. Rising Seismic Activity Trends in Turkey

Turkey has witnessed a marked rise in major seismic activity over the past two decades. The timeline shows that large earthquakes with a Moment Magnitude (Mw) greater than 6.5 have been recurring at unusually short intervals of about 4–7 years. This sequence—including major events in 2011, 2020, 2022, and the catastrophic 2023 Kahraman Maras earthquakes—challenges key assumptions underlying current seismic design philosophies, as illustrated in Fig.1[3,8]. Traditionally, code development assumes that the return period for design-level earthquakes is substantially longer than the functional lifespan of newly constructed buildings, thus permitting a degree of repairable damage. However, the short recurrence rate observed suggests that many structures will be subjected to multiple major seismic loadings within their design life. Crucially, observations from the 2023 Kahraman Maras earthquakes demonstrated widespread severe damage and collapse in numerous buildings that had been constructed after the implementation of the stricter 2018 seismic code revisions. This outcome directly challenges the efficacy and implicit performance guarantees of the existing regulations. The contradiction underscores a critical need for a paradigm shift in the Turkish seismic code, moving away from assumptions of long return periods and minimal repair and towards a genuine resilience-based approach that ensures post-event functionality.

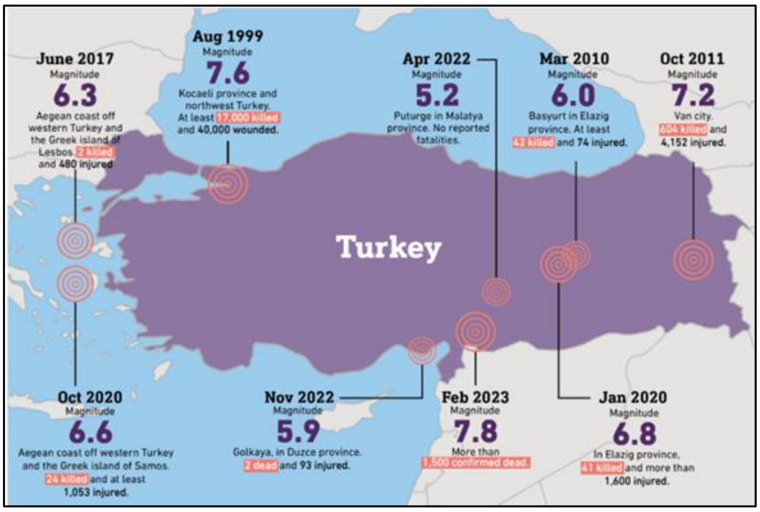


Figure 1 Significant earthquakes in Turkey in recent years [3]

3. Seismic Performance Failures in Recently Constructed Buildings

Despite code compliance, post-event reconnaissance shows that newly built structures exhibit common failures: brittle partition wall collapse, severe drift-related damage, and amplified resonance effects in tall buildings. Nonstructural systems (MEP, ceilings, facades) routinely fail due to inadequate consideration. Though structurally sound, many buildings were rendered functionally unusable, leading to vast economic losses and a critical shelter deficit. The limited adoption of available damping devices compounded these nonstructural performance issues. The following subsections outline the deficiencies in current seismic design codes of practice:

3.1. Nonstructural Walls and Seismic Resilience

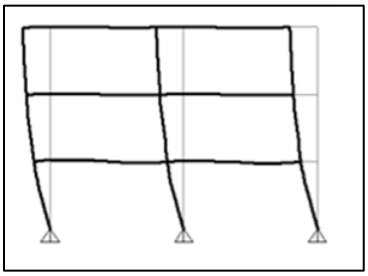
Unreinforced masonry (URM) partition walls are major seismic vulnerabilities, despite being classified as nonstructural. Their very low drift capacity (0.2–0.5%) means they fail early, causing loss of lateral resistance and dangerous out-of-plane collapse that creates significant debris and casualties. Critically, the unintended infill–frame interaction at low drifts often creates short-column effects and stiffness irregularities, which are primary triggers for soft-story building collapse. Consequently, the shift is toward seismically resilient partition systems such as cold-formed steel (CFS) or engineered wood panels. These modern systems offer higher ductility and deformation capacity, significantly reduced mass (lowering inertial forces), improved energy dissipation, and better anchorage integration. Adopting these alternatives mitigates URM flaws, supporting a low-damage design philosophy that enhances life safety and ensures rapid functional recovery and minimal structural downtime after major seismic events.

3.2. Damage Accumulation in Undamped Structures

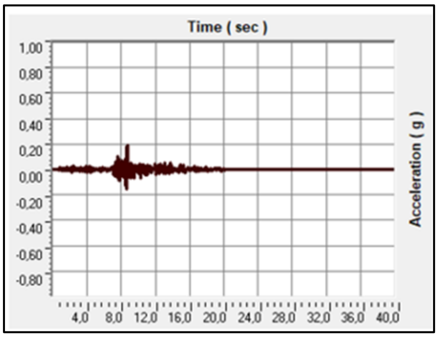
Modern seismic resilience demands that high-occupancy and mission-critical facilities (hospitals, data centers) maintain guaranteed post-earthquake operational functionality, requiring performance far beyond minimum life-safety standards. To achieve this, engineering practice is increasingly incorporating supplemental damping and seismic protection technologies, raising the effective damping ratio from the typical 5% up to 15–30% of critical damping. Key technologies include Viscous Fluid Dampers (VFDs), Friction Dampers, and Metallic Yield Dampers (like Buckling-Restrained Braces) which dissipate energy to reduce peak floor accelerations and interstory drift. Base Isolation systems, such as Lead-Rubber Bearings (LRBs), physically decouple the structure from ground motion, often achieving a 60–80% reduction in floor acceleration, effectively protecting sensitive nonstructural components. Despite these proven benefits—including lower internal forces, reduced drift, and decreased nonstructural damage—most international seismic codes still lack a mandatory minimum supplemental damping requirement even for critical facilities. This gap, driven by a traditional focus solely on collapse prevention, leaves large, flexible structures vulnerable to resonance effects and high drift demands [6,7]. Therefore, there is a clear imperative to adopt a resilience-based framework where supplemental damping is viewed as an essential, integral component of modern seismic design. Fig 2 shows a three-story frame with a natural frequency of 3.5 Hz nearly matched the 3.57 Hz dominant frequency of the Trinidad earthquake record, causing resonance. This resonance amplified the top-floor acceleration to four times the ground acceleration. Increasing the structural damping from 5% to 20% of critical damping successfully reduced the top-floor acceleration by approximately half.

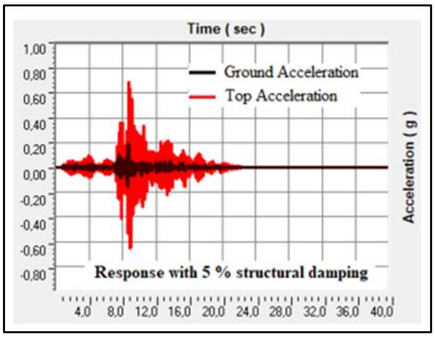
3.3. Response Modification Factors (R-Factors)

Response Modification Factors (R-factors) significantly reduce elastic seismic design forces (often R=6 to 8), relying on the assumption of substantial ductility, overstrength, and energy dissipation via inelastic deformation [4, 5]. This reduction, however, makes design highly sensitive to real-world deviations. A critical flaw is the presumption of ideal detailing quality and robust construction necessary for stable plastic hinge formation. In many high-seismicity regions, significant construction quality variability (e.g., poor concrete or rebar placement) prevents the structure from achieving the theoretical ductility assumed by the R-factor.

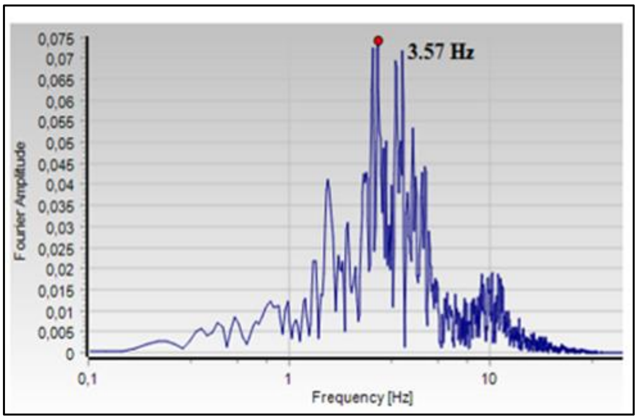


A) Three-story structural frame exhibits a fundamental natural frequency of 3.5 Hz

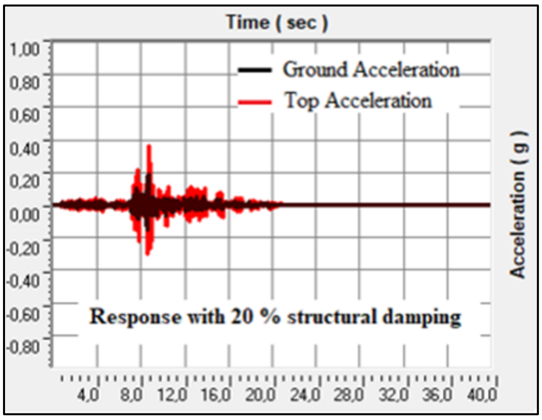




B) Time-history record of the Trinidad earthquakeC) Top acceleration response with 5 % damping



D) Fast Fourier Transform (FFT)



E) Top acceleration response with 20% damping

Figure 2 Comparative dynamic response of a three-story structure subjected to the Trinidad earthquake ground motion, illustrating the influence of 5% and 20% damping ratios

Additionally, R-factors assume a single, rare earthquake event, contradicting recent observations of shorter recurrence intervals and cumulative damage from multiple major seismic sequences. Field evidence consistently shows real buildings suffer premature failures (e.g., shear failures, brittle joints) below their theoretical capacity, often triggered by unintended nonstructural component interaction. Furthermore, R-factors typically ignore cyclic strength degradation and low-cycle fatigue from long-duration shaking. This persistent disparity between the idealized performance assumed by R-factors and actual observed structural behavior necessitates a methodological transition away from this over-reliance and toward explicit performance-based design and the adoption of low-damage technologies, frequently leading to a prescribed reduction in the applied R-value for highly important or heavily occupied buildings in high seismic zones, as noted by Karak ale and Layas [2], to minimize casualties and property loss.

4. Proposed Amendments to Seismic Resilience Code

The following amendments establish higher performance standards mandating a transition to resilience-based seismic design. These changes specifically target the mitigation of nonstructural hazards and address the performance deficiencies observed in structures subjected to major seismic events.

4.1. Nonstructural Partition Materials

4.1.1. Proposed Code Clause

"In high seismic hazard zones, the use of brittle partition materials such as hollow clay bricks or unreinforced masonry blocks is prohibited. Only ductile partition systems—such as cold-formed steel stud walls, engineered wood partitions, or 3D panel systems—shall be permitted."

4.2. Energy Dissipation for High-Occupancy Structures

4.2.1. Proposed Code Clause

"Buildings in high-seismic zones with high occupancy shall incorporate supplemental energy dissipation systems providing no less than 15% of critical damping. Damping devices may be integrated within partition walls, frames, or isolation systems."

4.3. Seismic Force Reduction Factors (R-Factors)

4.3.1. Proposed Code Clause

"For high-hazard zones, R-factors shall be reduced to values that ensure improved performance under major earthquakes, particularly for essential and newly constructed buildings. Recommended limits $R < 4$ for buildings requiring immediate occupancy or continued operation."

5. Conceptual and Methodological Framework for Resilience-Based Seismic Design

The proposed amendments mark a crucial evolution in seismic engineering, collectively shifting the design philosophy from a narrow life-safety–only objective toward a comprehensive framework that includes life safety, reduced injury rates, and sustained post-earthquake functionality and resilience. This shift acknowledges that merely preventing collapse is insufficient for modern societies where essential facilities (like hospitals and transportation hubs) must remain operational and minimize downtime to avoid cascading economic and social disruption. While enhanced requirements—such as stricter nonstructural criteria, advanced detailing, and the integration of supplemental damping technologies—may increase initial construction costs, these expenses are substantially offset by major long-term benefits. These advantages include significantly lower repair and reconstruction costs by preventing severe drift-related and nonstructural damage, improved occupant safety by reducing falling hazards and debris (primary injury contributors), and the preservation of building functionality that reduces income loss and reliance on emergency funding. However, achieving this resilience-focused transition requires coordinated action beyond just updating codes. Successful implementation hinges on consensus among regulatory bodies, comprehensive builder and contractor training to ensure correct execution of complex detailing and damping device installation, and, most critically, strengthening inspection and enforcement mechanisms to close the persistent gap between design intent and actual construction quality that has plagued performance in recent earthquakes. Furthermore, the framework needs validation through region-specific guidelines, analytical studies, and cost–benefit analyses to quantify the economic viability of enhanced performance for various building types. Ultimately, moving toward a resilience-based seismic design is essential for aligning structural performance objectives with societal expectations, minimizing long-term economic burdens, and guaranteeing the safety and well-being of occupants during and after a seismic event.

6. Conclusion

The traditional life-safety–only seismic design philosophy is fundamentally inadequate for protecting modern society and essential infrastructure against high and recurrent earthquake hazards.

Based on observed chronic deficiencies, three urgent amendments are proposed to shift toward a resilience-based framework

- Eliminate Brittle Partitions: Unreinforced masonry (URM) infills must be replaced by ductile, lightweight alternatives (like CFS framing) to prevent out-of-plane failure, debris hazards, and disproportionate functional downtime.
- Mandate Supplemental Damping: A minimum of 15% supplemental damping must be required for all high-occupancy and essential facilities (e.g., hospitals). Technologies like viscous fluid dampers or base isolation ensure post-earthquake functional performance by reducing floor accelerations and residual drifts.
- Recalibrate R-factors: Response Modification Factors (R-factors) must be reduced from the current high values (6–8). This will increase the design base shear, acknowledging that idealized ductility assumptions are often unmet in real-world construction, leading to more robust designs that can better withstand recurrent seismic events.

These reforms collectively prioritize life safety (reducing casualties and injuries), damage control, minimized downtime, and long-term functional recovery.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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