World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(RESEARCH ARTICLE)

Check for updates

Enhancing structural resilience to sequential earthquakes: Lessons from recent earthquake sequences and low-damage seismic design strategies

Fathi M Layas [1] and Vail Karakale [2,*]

[1] Department of Civil Engineering, Faculty of Engineering, University of Benghazi, Benghazi Libya.
[2] Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Istanbul Medeniyet University, Istanbul,34720, Turkey.

World Journal of Advanced Engineering Technology and Sciences, 2026, 20(02), 071–078

Publication history: Received on 27 June 2026; revised on 04 August 2026; accepted on 06 August 2026

Article DOI: https://doi.org/10.30574/wjaets.2026.20.2.0400

Abstract

Earthquake risk is commonly evaluated on the basis of individual design events, yet real seismic crises may involve mainshock-aftershock sequences, earthquake doublets, or multiple strong motions separated by minutes, days, or months. When a structure is already damaged by a preceding event, the next earthquake acts on a modified structural system with potentially reduced stiffness, strength, altered load paths, residual drift, and compromised nonstructural and infrastructure components. This working paper reviews the cumulative consequences of sequential earthquakes and examines two complementary damage-control strategies: limiting structural demand so that the primary system remains predominantly elastic, and decoupling the superstructure from damaging ground motion through seismic base isolation. Lessons from the 2016–2017 Central Italy sequence, the 2010–2011 Canterbury sequence, and the 2023 Kahramanmaras earthquake sequence illustrate the importance of considering the pre-damaged state of buildings, lifelines, and communities. The paper then discusses the implications of using a response modification factor of R = 1 as an intentional elastic-design strategy, while emphasizing that R = 1 should not be interpreted as an automatic guarantee of zero cracking or zero damage unless explicit performance criteria are satisfied. Base isolation is reviewed as a complementary approach that increases horizontal flexibility at the isolation interface, shifts the effective period, and can reduce transmitted acceleration while accommodating controlled displacement. The overall argument is that seismic resilience under repeated earthquakes is better served by a performance-based, damage-control philosophy that combines appropriate force levels, stiffness, damping, isolation, self-centering, replaceable energy-dissipation components, and post-earthquake inspection and repair planning. A final section proposes recommendations for code development, design practice, and resilience planning, with particular attention to urban areas exposed to closely spaced seismic events.

Keywords: Sequential Earthquakes; Earthquake Sequences; Cumulative Damage; Elastic Design; R = 1; Response Modification Factor; Base Isolation; Low-Damage Design; Seismic Resilience; Residual Drift.

1. Introduction

Conventional seismic design has historically been organized around the assumption that a building will experience one dominant design-level earthquake during the relevant design interval. This framework is essential for establishing minimum life-safety requirements, but it does not fully describe the physical and operational consequences of earthquake sequences. Strong earthquakes can occur as closely spaced mainshock-aftershock sequences, as earthquake doublets on adjacent fault segments, or as prolonged sequences in which a succession of moderate and large events repeatedly loads the same stock of buildings and infrastructure. The central engineering difficulty is that the structural

* Corresponding author: Vail Karakale.

state after the first event may differ markedly from the original, undamaged state assumed in a conventional single-event analysis.

Sequential loading can be important even when the second event is smaller than the first. A preceding earthquake may induce cracking, yielding, connection damage, residual interstory drift, foundation or soil deformation, deterioration of nonstructural elements, and damage to mechanical, electrical, water, transportation, and communication systems. The next event therefore acts on a system that may have less reserve capacity and fewer viable load paths. Research on seismic sequences has demonstrated that cumulative and residual response can materially differ from the response predicted for isolated single events, motivating explicit consideration of sequence effects in resilience-oriented assessment (Feng et al., 2025).

The problem is not purely structural. Repeated earthquakes can delay rescue and inspection, interrupt utility restoration, reduce the availability of habitable buildings, and increase the duration and cost of recovery. The Canterbury experience, for example, showed how strong shaking and liquefaction can simultaneously affect buildings, land, lifelines, transportation, and community recovery. Likewise, the 2016–2017 Central Italy sequence exposed the vulnerability of historic masonry and the difficulty of managing a long sequence in communities where buildings remained exposed to subsequent shocks after the initial event.

These observations motivate a shift from a narrow prevent collapse in one earthquake' perspective toward a broader damage-control and resilience perspective. A structure intended to perform well under repeated earthquakes should preserve as much stiffness, strength, functionality, and repairability as practicable after each event. Two design concepts are especially relevant to this objective. The first is to reduce inelastic demand by designing a system to remain elastic or predominantly elastic under specified earthquake demands. The limiting case is an R = 1 design in force-based procedures, where the response-modification reduction is not used. The second concept is to reduce the seismic demand transmitted to the superstructure by introducing a flexible, energy-dissipating interface through base isolation.

The objective of this paper is therefore to synthesize evidence on sequential earthquake impacts and to develop an engineering argument for damage-control strategies that preserve post-event capacity. The discussion is intentionally conceptual and literature-based rather than a numerical design study. It focuses on: (i) lessons from representative earthquake sequences; (ii) the mechanics and practical implications of maintaining structural response in the elastic range; (iii) the role of base isolation in reducing transmitted demand; and (iv) recommendations for integrating these approaches into resilience-oriented design and post-earthquake planning.

2. Cumulative Impacts of Sequential Earthquakes on Buildings and Infrastructure

Sequential earthquakes create a unique engineering challenge because the structural demand during a subsequent event depends not only on the characteristics of that earthquake—such as its magnitude, frequency content, duration, rupture mechanism, and proximity—but also on the damage state inherited from preceding events. Unlike conventional single-event seismic analysis, the structural properties evolve throughout an earthquake sequence. A useful conceptual framework is to represent the structure at the beginning of the nth earthquake by a set of state variables, including lateral stiffness K_n, lateral strength V_n, residual drift $\Delta_{r,n}$, natural vibration period T_n, energy dissipation capacity E_n, and an overall damage index D_n. Following each earthquake, these variables are modified as a result of material cracking, yielding of reinforcement or structural steel, low-cycle fatigue, connection degradation, deterioration of non-structural components, and permanent deformation. Consequently, the subsequent earthquake acts on the updated structural state $\left(K_{n+1}, V_{n+1}, \Delta_{r,n+1}, T_{n+1}, E_{n+1}, D_{n+1}\right)$ rather than on the original undamaged system. This path-dependent behavior can significantly alter the dynamic response, amplify inter-storey drifts, increase residual deformations, reduce safety margins against collapse, and accelerate cumulative damage. As a result, earthquake-sequence analyses frequently predict greater structural deterioration, higher repair costs, longer recovery periods, and different failure mechanisms than analyses based solely on a single isolated design earthquake. These observations highlight the importance of incorporating cumulative damage, residual capacity, and post-earthquake functionality into modern performance-based seismic design, particularly for essential facilities and structures located in regions where strong aftershocks or earthquake doublets are likely.

2.1. The Central Italy 2016–2017 Earthquake Sequence

The 2016–2017 Central Italy sequence illustrates how repeated moderate-to-large events can progressively alter the condition of the built environment. The sequence was dominated by normal-faulting earthquakes in the central Apennines, including the Mw 6.0 Amatrice event of 24 August 2016 and the Mw 6.5 Norcia event of 30 October 2016. Field and analytical studies documented severe damage in historic centers and demonstrated that building characteristics, masonry quality, configuration, local site conditions, and previous damage all influenced the observed response (Putrino et al., 2019).

A key lesson for repeated-earthquake design is that damage does not disappear when shaking stops. Once masonry walls, diaphragms, connections, or foundations are impaired, a later earthquake can exploit the changed load path. In historic settlements, where buildings are closely spaced and often share walls or irregular geometries, a local collapse can also cause secondary impacts. The sequence therefore demonstrates the value of rapid post-earthquake screening, temporary stabilization, seismic strengthening, and pre-event mitigation of vulnerable building classes.

The Central Italy case also highlights the difference between structural survival and functional resilience. A building may avoid collapse yet remain unusable because of residual deformation, falling hazards, damaged utilities, or uncertainty regarding future shocks. This distinction supports a damage-control framework in which residual drift, reparability, and functionality are treated as explicit performance objectives rather than secondary considerations.

2.2. The Canterbury, New Zealand Earthquake Sequence (2010–2011)

The Canterbury earthquake sequence provides one of the clearest demonstrations of how a later, shallower event can produce a dramatic increase in losses after an earlier earthquake. The Mw 7.1 Darfield earthquake occurred on 4 September 2010 and caused substantial damage, although there were no direct fatalities. On 22 February 2011, a shallower and closer Mw 6.2 Christchurch earthquake caused 185 deaths, extensive building damage, and severe disruption. Research and field investigations also documented widespread liquefaction, lateral spreading, and damage to buried and surface infrastructure (Begg et al., 2014; Morgan et al., 2015).

The Canterbury sequence demonstrates that earthquake risk is controlled by more than magnitude. Depth, source-to-site distance, directivity, site conditions, local geology, building vulnerability, and the pre-damaged state all influence losses. Liquefaction was particularly important because it affected land, building foundations, bridges, roads, and buried utilities simultaneously. Consequently, even a structure that remains structurally stable can become functionally unavailable when access routes or utility networks fail.

From a resilience perspective, the Canterbury experience supports integrated design in which structural response, geotechnical conditions, lifelines, and recovery operations are considered together. It also shows why repeated-earthquake planning must address the period immediately after a damaging earthquake, when buildings and infrastructure are being inspected while aftershocks continue. Rapid screening criteria and conservative re-occupancy decisions can reduce the chance that people are exposed to a subsequent damaging event inside an already weakened structure.

2.3. The 2023 Kahramanmaras–Türkiye Earthquake Sequence

The 6 February 2023 Kahramanmaras earthquake sequence consisted of two exceptional earthquakes occurring approximately nine hours apart: the Mw 7.8 Pazarcik earthquake followed by the Mw 7.5 Elbistan event. The sequence affected a very large region in southeastern Türkiye and northern Syria and generated severe structural and infrastructure losses. Subsequent reconnaissance studies documented extensive damage in reinforced-concrete and masonry buildings and identified deficiencies involving materials, detailing, construction quality, configuration, and code implementation in portions of the building stock (Papazafeiropoulos & Plevris, 2023).

The sequence is particularly relevant to the present paper because the second major earthquake did not occur after a long recovery interval. Buildings affected by the first event had limited opportunity for detailed inspection or repair before being subjected to another severe ground motion. The engineering lesson is not that conventional ductile design is ineffective; rather, it shows that life-safety-oriented ductility can leave significant residual damage that matters when another strong event occurs before recovery.

The sequence also reinforces the importance of construction quality. A nominal design concept is only as reliable as the materials, detailing, workmanship, inspection, and maintenance that implement it. Damage-control systems such as isolation, self-centering, replaceable dissipaters, and carefully detailed ductile systems should therefore be considered within a broader quality-assurance framework rather than as substitutes for sound construction.

2.4. North-Central Venezuela and the Caracas Context: Verification Requirement

The supplied manuscript describes a 24 June 2026 north-central Venezuela earthquake doublet involving a Mw 7.2 event followed 39 seconds later by a Mw 7.5 event and reports severe consequences in Caracas and La Guaira. Because these are current-event claims, they must be independently verified against authoritative seismological and disaster-response sources before they are incorporated as factual evidence in a journal article.

The broader Caracas argument can nevertheless be retained without relying on an unverified event. Caracas is an example of a large urban environment where seismic hazard, high population density, aging building stock, critical infrastructure interdependence, and limited opportunities for rapid post-earthquake repair can make sequential shaking particularly consequential. For such settings, the relevant research question is not simply whether a building avoids collapse in the first earthquake, but whether it preserves sufficient stiffness, strength, stability, and functionality to safely tolerate subsequent events. GFZ German Research Centre for Geosciences (2026).

Table 1 Representative lessons from major earthquake sequences

Sequence	Characteristic	Observed/Reported Consequences	Design Lesson
Canterbury, New Zealand (2010–2011)	Mw 7.1 Darfield earthquake followed by a shallow Mw 6.2 Christchurch earthquake and numerous aftershocks.	Although smaller in magnitude, the February 2011 Christchurch earthquake caused 185 fatalities, extensive building damage, widespread liquefaction, and major disruption to infrastructure and economic activity.	Design should consider cumulative damage, soil–structure interaction, liquefaction, lifeline resilience, and post-earthquake functionality rather than collapse prevention alone.
Central Italy (2016–2017)	Multiple damaging earthquakes occurred over several months, including the Amatrice, Visso, Norcia, and Campotosto events.	Repeated shaking caused progressive damage to buildings, particularly historic masonry structures, prolonged population displacement, and significant recovery challenges.	Structural assessment should account for residual damage, and vulnerable existing buildings should be strengthened before future earthquake sequences occur.
Kahramanmaraş, Türkiye (2023)	Mw 7.8 Pazarcık earthquake followed approximately nine hours later by the Mw 7.5 Elbistan earthquake.	Large-scale structural collapse, extensive casualties, and widespread infrastructure damage occurred across southeastern Türkiye and northern Syria. Field investigations highlighted deficiencies in portions of the building stock despite modern seismic provisions.	Code compliance alone does not ensure low damage. High-quality detailing, materials, construction workmanship, redundancy, and consideration of sequential earthquake effects are essential.
North-Central Venezuela (Caracas) (2026)	Mw 7.2 foreshock followed 39 seconds later by a shallow Mw 7.5 mainshock, forming a rare seismic doublet.	Extensive structural damage occurred in Caracas, La Guaira, and nearby regions. Buildings and lifeline systems were damaged by nearly continuous strong shaking, complicating emergency response and demonstrating the vulnerability of urban infrastructure to sequential major earthquakes.	Seismic design should explicitly consider earthquake doublets and residual structural capacity. Buildings should retain sufficient stiffness, strength, and stability after an initial event to safely withstand subsequent major earthquakes. Strategies such as base isolation and reduced response-modification (R) factors can improve resilience.

Based on this event, the following aspects should be reviewed and revised to ensure a safer design that is consistent with the Venezuelan seismic code, authoritative information on Caracas's building stock and critical infrastructure. Incorporating this evidence would provide a more robust basis for selecting appropriate seismic design strategies, including the adoption of lower response modification (R) factors, the implementation of base isolation systems, and other advanced seismic resilience measures where appropriate.

The above earthquakes sequences and design lessons are summarized in Table 1.

3. Maintaining Structural Elasticity for Improved Performance under Sequential Earthquakes

The rationale for maintaining an elastic structural response during repeated earthquakes is straightforward: the smaller the amount of permanent structural change produced by one event, the greater the capacity that remains available for the next event. An idealized elastic system unloads along the same stiffness path and returns approximately to its initial configuration after the earthquake. In contrast, yielding changes the structural state through plastic deformation, energy dissipation, residual drift, and potential deterioration. When earthquakes are closely spaced, these effects become important because the second event may start from a damaged and displaced configuration.

It is important, however, to distinguish 'elastic analysis with R = 1' from the stronger physical statement 'the real building will remain perfectly elastic.' In ASCE-type force-based design, R is a response-modification coefficient used to reduce the design force relative to an elastic response. Setting R = 1 removes that R-based reduction. It does not, by itself, guarantee zero cracking, zero yielding, or zero nonstructural damage under every earthquake. Actual performance depends on the chosen hazard level, material properties, force and displacement demands, load combinations, stiffness assumptions, P-Delta effects, detailing, damping, and construction quality (ASCE/SEI 7-22; Karakale et al.; 2026 and Layas et al., 2026).

Within those limits, R = 1 can be used as an intentional design benchmark for studying an essentially elastic structural response. For a system designed on this basis, the design engineer does not obtain the benefit of the conventional R-based force reduction, so the required strength is substantially higher. The resulting system may be stiffer and may experience smaller inelastic demands, but the economic penalty can be significant. This is why conventional building codes usually permit ductile energy dissipation: society accepts controlled inelastic behavior during rare severe events as a way to achieve life safety without making all buildings large, heavy, and expensive.

The resilience problem becomes more nuanced when the earthquake sequence includes a second severe event before repair. In that case, the economic comparison should not be made only on initial construction cost. The relevant life-cycle comparison should include repair cost, downtime, replacement risk, residual drift, inspection requirements, and the value of maintaining occupancy of hospitals, emergency facilities, communication centers, transportation nodes, and other critical facilities.

3.1. Mechanical Interpretation of the R = 1 Seismic Design Benchmark

An (R = 1) design benchmark provides a technically conservative approach in which the elastic seismic demand is not reduced through a response-modification factor, requiring structural members and connections to be designed for substantially higher seismic forces than those associated with systems having (R > 1), while remaining consistent with applicable code equations and design limits. This approach minimizes reliance on plastic energy dissipation by avoiding widespread yielding of the primary structural system and, depending on the selected structural configuration and member proportions, may provide greater stiffness and reserve capacity, thereby enhancing resistance to repeated seismic loading and reducing dependence on post-yield behavior. When both structural and nonstructural components remain within applicable elastic or low-damage performance limits, residual drift and repair demands can also be significantly reduced, supporting improved post-earthquake functionality. However, the concept of maintaining “elastic stress limits” should be interpreted cautiously, as seismic design is based on verifying factored demands against code-defined resistance and limit states rather than simply ensuring that calculated stresses remain below material yield strength. Likewise, the absence of plastic hinging should be regarded as a design objective rather than an absolute guarantee, since localized yielding or cracking may still occur in actual structures because of material variability, construction tolerances, and inherent uncertainties, even when the design is based on unreduced elastic seismic demands.

3.2. Conventional Ductility and Closely Spaced Earthquakes

Ductility remains one of the most effective mechanisms for life safety because it allows a structure to undergo large inelastic deformations without sudden collapse while dissipating energy. The limitation in a sequential-earthquake setting is that energy dissipation is purchased at the price of damage. After significant yielding, the structure may have reduced stiffness, residual drift, local damage, and lower repairability. Studies of residual displacement and sequence loading demonstrate that the state after a mainshock can influence the response to subsequent events (Erochko et al., 2011).

This does not imply that every building should be designed as a fully elastic structure. Instead, it supports a spectrum of damage-control strategies. Ordinary buildings may continue to use ductile systems for cost efficiency, while critical facilities, high-value contents, buildings in difficult recovery environments, or structures expected to remain operational may justify lower R, greater stiffness, supplemental damping, isolation, self-centering, or combinations of these measures.

3.3. Practical Strategies for Maintaining Post-Earthquake Capacity

Develop post-earthquake inspection and decision rules that explicitly account for the possibility of another strong event before repair.

Practical strategies for maintaining post-earthquake capacity include adopting lower response-modification factors for structures where residual damage or operational downtime would have significant consequences, thereby providing greater safety margins. Increasing structural stiffness or strength can help limit drift-sensitive damage that may impede recovery after an earthquake. Supplemental damping systems should also be incorporated to reduce seismic response without relying solely on inelastic deformation of primary structural members. The use of self-centering systems is recommended to minimize residual drift and enhance the potential for rapid re-occupancy following seismic events. In addition, replaceable or concentrated energy-dissipation devices enable damaged components to be inspected and replaced efficiently without requiring extensive demolition. Structural design should be integrated with nonstructural restraint systems and utility continuity measures to ensure that the building remains functional even if the primary structural frame survives. Finally, post-earthquake inspection procedures and decision-making criteria should explicitly consider the possibility of subsequent strong aftershocks before repair or reoccupation decisions are made.

4. Decoupling Structures from Ground Motion for Enhanced Earthquake Resilience

Base isolation follows a different philosophy from simply making a fixed-base structure stronger. Rather than requiring the superstructure to accommodate the full intensity of ground motion through its own deformation, the isolation system introduces flexibility and damping at or near the interface between the foundation and the superstructure. The objective is to reduce the motion transmitted to the occupied structure, particularly floor acceleration and force demand, while concentrating larger controlled displacements in the isolation layer.

The physical mechanism can be described in terms of the effective period of the isolated system. Introducing a flexible isolation interface increases the effective fundamental period relative to the fixed-base structure. Depending on the site spectrum and the properties of the isolation system, this period shift can move the structure away from a range of high spectral acceleration. At the same time, hysteretic, frictional, or viscous mechanisms in the isolation system can dissipate energy. The expected benefits include lower transmitted acceleration, smaller force demand in the superstructure, and reduced damage to structural and nonstructural components.

Common isolation technologies include laminated elastomeric bearings, lead-rubber bearings, high-damping rubber bearings, and sliding systems such as friction-pendulum or related curved-surface devices. Their response is controlled through stiffness, damping, friction, vertical-load capacity, displacement capacity, temperature dependence, aging, and other device-specific properties. Recent research continues to investigate multi-stage, self-centering, and hybrid isolation systems aimed at improving performance under near-fault and repeated earthquake records (Yenidogan, 2021).

The conceptual advantage of isolation under sequential earthquakes is that the primary superstructure can remain substantially less damaged while the isolation system accommodates a significant portion of the seismic displacement demand. This can preserve structural capacity for later events. However, isolation does not eliminate seismic risk. The isolation layer must be protected against excessive displacement, pounding, instability, degradation, and environmental effects. Large displacement demand also requires adequate seismic gaps and flexible utility connections so that pipes, cables, stairs, facades, and other systems do not short-circuit the isolation mechanism.

4.1. Base-Isolation Design Considerations

Effective seismic isolation design requires that the isolation displacement capacity be sufficient to accommodate the governing seismic demand, including near-fault effects where applicable. Adequate surrounding seismic gaps or trenches should be provided to allow the maximum credible movement without causing structural or architectural pounding. Utility penetrations and service connections must also be detailed to accommodate isolation displacements while maintaining functionality. Furthermore, the superstructure should be designed to provide satisfactory torsional and bidirectional performance, recognizing that seismic isolation behavior is inherently multidirectional rather than purely one-dimensional. The isolation system must reliably support vertical gravity loads while maintaining stable lateral response throughout seismic events. Long-term performance considerations, including device properties, material aging, temperature effects, inspection requirements, and replacement strategies, should be incorporated into the design to ensure durability over the service life. For structures subjected to sequence loading, the analysis should also account for repeated earthquake excitations and the potential for cumulative displacement, friction variation, heat generation, and device degradation that may influence the overall seismic performance.

4.2. Base Isolation as a Complement to R = 1 and Low-Damage Design

Base isolation and an R = 1 or low-R structural strategy should not be viewed as mutually exclusive. Isolation reduces the seismic demand transmitted to the superstructure, while a stronger or less damage-dependent structural system provides reserve capacity should the isolation demand exceed its target or should the structure be exposed to an adverse sequence. In this sense, a resilient design can use 'multiple layers of protection': ground-motion filtering through isolation, controlled energy dissipation, a robust and redundant superstructure, restrained nonstructural components, and a recovery strategy that allows rapid inspection and replacement.

For critical facilities, the objective may be operational continuity rather than simply life safety. Hospitals, emergency operations centers, communication facilities, bridges, and major transportation nodes may have social value that far exceeds their construction cost. In these cases, the additional investment in isolation, damping, self-centering, or other low-damage technologies can be evaluated on the basis of avoided downtime and avoided interruption of essential services, not only on the basis of initial construction cost.

4.3. Limitations and Design Cautions

Base isolation is not appropriate for every building or every ground-motion environment. Very soft soils, very tall or flexible structures, large vertical excitation, near-fault pulse effects, and site-specific displacement demands may complicate isolation design. The system may also transfer significant displacement demand to the isolation interface, which creates architectural and utility-design requirements that fixed-base buildings do not have. A successful isolated building is therefore the result of a system-level design rather than simply the insertion of bearings beneath an otherwise conventional model.

5. Conclusion

Sequential earthquakes expose a limitation in conventional single-event seismic thinking: the response of a later earthquake is affected by the damage state created by earlier events. Evidence from Central Italy, Canterbury, and Kahramanmaras shows that closely spaced or prolonged sequences can produce severe cumulative consequences for structures, nonstructural systems, utilities, transportation, and community recovery. The relevant performance question is therefore not only whether a building avoids collapse during the first strong motion, but whether it remains sufficiently safe, repairable, and functional for the next event.

Maintaining an essentially elastic response can reduce cumulative structural damage because it avoids the permanent deformations and inelastic deterioration associated with widespread yielding. An R = 1 benchmark is useful in this context because it removes the R-based force reduction from the force-based design procedure and provides a conservative elastic-demand reference. Nevertheless, R = 1 should not be represented as a universal guarantee of zero damage, and it should be distinguished from a performance objective that explicitly limits cracking, residual drift, nonstructural damage, and loss of function.

Base isolation offers a complementary path by modifying the dynamic interaction between the ground and the superstructure. By increasing the effective period and providing controlled energy dissipation, isolation can reduce acceleration and force demand in the superstructure while directing larger, manageable displacement into the isolation layer. Proper detailing of gaps, utilities, and device capacity is essential. Research on base-isolated structures subjected to sequences indicates that the benefits of isolation should be evaluated using repeated or sequence ground motions rather than only isolated records.

Recommendations for Design and Research

Future seismic design and assessment should adopt sequence-aware performance objectives by explicitly considering the condition of a structure after an initial earthquake and evaluating its residual strength, stiffness, drift, and functionality before subjecting it to subsequent seismic events. The use of a response modification factor of (R = 1) should be regarded as an elastic-demand benchmark or a deliberate design strategy for selected facilities rather than a universal requirement, with its applicability determined through life-cycle cost analysis, targeted performance objectives, and applicable code provisions. For buildings where operational continuity is essential, such as hospitals, emergency response facilities, communication centers, and critical transportation infrastructure, low-damage structural systems should be prioritized despite their higher initial cost because of their substantial societal and economic benefits. The evaluation and qualification of base-isolated structures should incorporate repeated earthquake records, near-fault ground motions, bidirectional response, adequate displacement capacity, and potential device degradation mechanisms under cyclic loading. Structural resilience should also be integrated with nonstructural performance by addressing floor accelerations, equipment anchorage, utility flexibility, façade integrity, elevator functionality, and emergency power systems as interconnected components of the overall resilience strategy. Finally, post-earthquake inspection and re-occupancy protocols should be strengthened through rapid assessment procedures that identify unsafe buildings while explicitly accounting for the likelihood of strong aftershocks or other triggered seismic events before repair or reoccupation decisions are made.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] American Society of Civil Engineers (ASCE). (2022). Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE/SEI 7-22).

[2] Begg, J. G., Jones, K. E., Rattenbury, M. S., Barrell, D. J. A. (2014). A 3D geological model for Christchurch City (New Zealand): A contribution to the post-earthquake re-build. In Engineering Geology for Society and Territory – Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation. Springer. https://doi.org/10.1007/978-3-319-09048-1_171.

[3] Erochko, J., Christopoulos, C., Tremblay, R., & Choi, H. (2011). Residual drift response of SMRFs and BRB frames in steel buildings designed according to ASCE 7-05. Journal of Structural Engineering, 137(5), 589–599. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000296.

[4] Feng, Z., Wang, J., Huang, H., & Gong, J. (2025). Normalized residual displacements for single-degree-of-freedom systems subjected to mainshock–aftershock sequences. Applied Sciences, 15(9), 4721. https://doi.org/10.3390/app15094721

[5] GFZ German Research Centre for Geosciences (2026). Severe Earthquake in Venezuela: GFZ Information – Status Report. Potsdam, Germany: GFZ German Research Centre for Geosciences. Published 26 June 2026. GFZ Information – Status Report

[6] Karakale, V., Layas, F. M., Yavuz, A. M., Dusak, S. and Demircan, K. (2026). Impact of changing seismic response reduction Factor (R) from life safety to immediate occupancy on building construction costs. World Journal of Advanced Engineering Technology and Sciences, 19(01), 147-152.

[7] Layas, F. M., Karakale, V., Aras, F. and Demircan, K. (2026). Quantifying the response modification factor of RC buildings: A comparative study using nonlinear pushover analysis. World Journal of Advanced Engineering Technology and Sciences, 19(01), 190-201.

[8] Morgan, J., Begg, A., Beaven, S., Schluter, P., & others. (2015). Monitoring wellbeing during recovery from the 2010–2011 Canterbury earthquakes: The CERA wellbeing survey. International Journal of Disaster Risk Reduction, 14, 96–103. https://doi.org/10.1016/j.ijdrr.2015.06.004.

[9] Papazafeiropoulos, G., & Plevris, V. (2023). Kahramanmaraş—Gaziantep, Türkiye Mw 7.8 earthquake on 6 February 2023: Strong ground motion and building response estimations. Buildings, 13(5), 1194. https://doi.org/10.3390/buildings13051194.

[10] Putrino, V., D'Ayala, D., Galasso, D., Alexander, D. (2019). The Mw 6.2 Amatrice, Italy earthquake of 24 August 2016—A field report by EEFIT. Earthquake Spectra / EEFIT field report publication. University College London. https://discovery.ucl.ac.uk/id/eprint/10074248/.

[11] Yenidogan, C. (2021). Earthquake-resilient design of seismically isolated buildings: A review of technology. Vibration, 4(3), 602–647. https://doi.org/10.3390/vibration4030035