

SEISMIC VULNERABILITY ASSESSMENT AND STRENGTHENING APPROACHES FOR EXISTING MULTISTOREY BUILDINGS

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ABSTRACT

Earthquakes continue to expose a persistent gap between the seismic demand imposed on the built environment and the capacity of buildings constructed before modern seismic codes were enforced. This review synthesizes three decades of research on the seismic vulnerability assessment and strengthening of existing multistorey buildings, drawing on empirical, analytical, and data-driven approaches reported in the literature. The paper traces the evolution of assessment methodology from first-generation rapid visual screening procedures, through mechanics-based tools such as pushover analysis and fragility curve construction, to the recent emergence of machine-learning-assisted vulnerability classification. It also reviews the principal strengthening techniques applied to deficient reinforced concrete and masonry stock, including concrete and steel jacketing, fibre-reinforced polymer and textile-reinforced mortar overlays, base isolation, and supplemental damping, weighing their structural effectiveness against cost, disruption, and durability concerns. Particular attention is given to configuration-driven weaknesses common in multistorey construction, notably soft and open ground storeys, short-column effects, plan irregularity, and pounding between adjacent blocks, which recur across case studies from India, Italy, Turkey, and other seismically active regions. A structured methodology guided the literature selection and classification underlying this review. The critical analysis that follows identifies where assessment methods diverge in accuracy and practicality, and where retrofitting research remains fragmented across material types rather than integrated at the building-system level. The review concludes that combining rapid screening for prioritization with performance-based assessment for design, supported by increasingly capable data-driven tools, offers the most credible path toward large-scale seismic risk reduction in existing multistorey building stock, though data scarcity and regional code disparities remain unresolved obstacles.

Keywords: *Seismic vulnerability¹, Existing buildings², Rapid visual screening³, Pushover analysis⁴, Fragility curves⁵, Seismic retrofitting⁶, Structural strengthening⁷*

1. INTRODUCTION

1.1 Seismic Risk and the Ageing Building Stock

Most of the world's seismic risk is not carried by buildings that will be built tomorrow; it is carried by buildings that were built decades ago, under design codes that either ignored lateral seismic loading or treated it as a minor design case. A large share of urban multistorey construction across earthquake-prone regions predates the seismic provisions now considered standard practice, meaning that reinforcement detailing, ductility, and lateral load paths were never explicitly designed for strong ground shaking [1], [2]. When strong earthquakes strike populated regions, the resulting toll is rarely a story about ground motion intensity alone. The 2023 Kahraman Maras earthquakes in Türkiye, for instance, produced widespread structural collapse across eleven provinces and underscored how much of the damage traced back to substandard construction practices in mid-rise reinforced concrete buildings rather than to unprecedented shaking [26]. Similar patterns have recurred in India, Nepal, Italy, and Indonesia, where post-earthquake reconnaissance consistently points to identifiable, and in principle correctable, structural deficiencies.

1.2 Why Multistorey Buildings Are Distinctly Vulnerable

Multistorey buildings introduce vulnerability mechanisms that are less pronounced in low-rise construction. Open ground storeys used for parking or commercial frontage create a soft-storey condition in which lateral stiffness drops sharply at one level, concentrating drift demand and often triggering storey collapse before upper floors are meaningfully engaged [20], [21]. Masonry infill panels, frequently treated as non-structural in design calculations, in practice alter stiffness distribution, and their irregular placement produces short-column effects and torsional response that designers did not anticipate [22]. Height also amplifies the consequences of plan irregularity, re-entrant corners, and inadequate separation gaps between adjacent structures, since pounding damage tends to concentrate at floor levels where neighbouring buildings have mismatched storey heights [11]. These mechanisms are well documented individually, but they rarely act in isolation in a real building, which is part of why vulnerability assessment for multistorey stock has proven harder to standardize than for simpler low-rise typologies.

1.3 Objectives and Structure of This Review

This review is organized as a meta-analysis of prior research rather than as new experimental or analytical work. Its purpose is threefold: first, to consolidate the assessment methodologies that have been proposed for existing multistorey buildings, spanning empirical screening, mechanics-based evaluation, and emerging data-driven techniques; second, to summarize the strengthening and retrofitting approaches that have been studied for reinforced concrete and masonry systems, along with the trade-offs reported for each; and third, to critically compare these bodies of work to identify where consensus exists, where methods conflict, and where research gaps remain unaddressed. The remaining sections proceed as follows: Section 2 surveys the assessment and strengthening literature by category; Section 3 describes the methodology used to compile and classify the reviewed sources; Section 4 offers a critical analysis of strengths and weaknesses across the surveyed work; Section 5 discusses broader implications and unresolved questions; and Section 6 concludes.

2. SURVEY OF PAST WORK

Empirical and rapid screening methods. The earliest and still most widely deployed vulnerability assessment tools are rapid visual screening (RVS) procedures, developed for situations where thousands of buildings must be triaged with limited time and budget. The FEMA-driven RVS framework, adapted for Indian conditions by Jain et al., combined sidewalk surveys of fifteen to thirty minutes with a scoring system tied to the capacity spectrum method underlying ATC-40, allowing engineers to flag buildings for more detailed study without performing full structural analysis on each one [9], [16]. Later adaptations extended this logic to Shillong, Dhaka, and parts of Pakistan, incorporating locally relevant parameters such as soil type, seismic zone, soft-storey presence, and building age into the scoring rubric [17], [18]. A parallel line of work assigned a quantitative structural score to RC frame buildings designed under Indian standards, calibrating the score against nonlinear pushover results generated for archetype buildings so that RVS output would correlate more closely with actual collapse probability rather than relying purely on qualitative judgment [19]. In Europe, comparable empirical index methods, including the RISK-UE vulnerability index and the GNDT approach, were developed specifically for masonry stock and have since been extended to reinforced concrete typologies in Portugal, Morocco, and Italy [1], [21].

Mechanics-based and analytical approaches. Where RVS methods trade precision for speed, analytical approaches attempt to model actual structural behaviour. Nonlinear static pushover analysis, calibrated against capacity spectra defined in ATC-40 and FEMA 356, remains the dominant tool for evaluating performance levels of individual buildings, particularly for diagnosing soft-storey and short-column failure mechanisms in RC frames [12], [13], [16]. Fragility curves extend this logic to populations of buildings by expressing the probability of exceeding a given damage state as a function of ground motion intensity, typically following the log-normal formulation adopted in the HAZUS methodology [14], [23]. Studies applying HAZUS-based fragility curves to cities such as Semnan in Iran have shown that model building types calibrated for one region do not transfer cleanly to another, since local construction practice, material quality, and code enforcement history all shift the fragility parameters [24]. More recent work has proposed alternative vulnerability index formulations tuned specifically to collapse limit states, arguing that existing standards under-specify the operative procedure needed to move from a qualitative vulnerability class to a quantitative collapse probability [2]. Instrumented approaches add another layer, using wireless sensor networks and modal identification to calibrate finite element models of specific buildings, an approach demonstrated on a reinforced concrete school building in Italy where sensor data was used to validate the vulnerability assessment before proposing an exoskeleton retrofit [3].

Strengthening and retrofitting techniques. The retrofitting literature separates fairly cleanly into local, element-level interventions and global, system-level interventions. At the element level, concrete jacketing was the earliest widely adopted technique, restoring or enlarging a damaged or under-designed column or beam section with additional concrete and reinforcement, though it adds mass and stiffness and can be disruptive to occupants [9]. Steel jacketing offers similar strength gains with less added mass but is comparatively unpopular in practice because of cost and detailing demands [9]. Fibre-reinforced polymer (FRP) wrapping has become the most extensively studied alternative, valued for its high strength-to-weight ratio, minimal disruption, and ease of installation, though it performs poorly under fire exposure and requires skilled application [9], [15]. Comparative reviews synthesizing more than a hundred experimental and numerical studies report that FRP retrofitting can

raise lateral load capacity by up to roughly forty percent and shear strength by thirty to eighty percent relative to unretrofitted members, while cutting the added structural weight associated with steel jacketing by half or more [8]. Textile-reinforced mortar has emerged as a comparable alternative to FRP that avoids some of its durability drawbacks, and has been benchmarked directly against FRP jacketing in state-of-the-art reviews [6]. At the system level, base isolation decouples the superstructure from ground shaking using bearings such as lead-rubber devices, and controlled cyclic testing comparing RC jacketing, steel jacketing, and lead-rubber base isolation on RC frames found that isolation prevented beam reinforcement yielding and redirected damage away from the primary structure into replaceable isolation components [11]. Supplemental bracing, added shear walls, and passive energy dissipation systems round out the global intervention toolkit, each altering the building's stiffness or damping rather than the strength of individual members [22].

Emerging data-driven approaches. A more recent strand of research applies machine learning to problems that were previously handled through fragility curves or manual screening. Artificial neural networks, random forests, and classification and regression trees have all been trained to predict RC building damage states or collapse status directly from structural and ground-motion features, reporting classification accuracies in the eighty to ninety percent range on the datasets tested [25], [27], [30]. Similar approaches have been applied to masonry building stocks in Türkiye following the 2023 earthquakes, using externally observable building properties to classify risk without requiring detailed structural analysis of every building in a large inventory [26]. Convolutional neural networks trained on street-level imagery have even been proposed for automated building typology classification at city scale, aiming to make RVS-style screening faster and less dependent on trained surveyors [29]. These methods are promising for large-scale prioritization but remain constrained by the size and regional specificity of the training datasets available, a limitation echoed across nearly every machine-learning study reviewed.

3. METHODOLOGY

This review followed a structured but qualitative meta-analytic process rather than a formal systematic-review protocol with pre-registered search strings. Relevant literature was identified through targeted searches of major engineering databases and publisher platforms, focusing on peer-reviewed journal articles, conference papers, and technical guideline documents published primarily between 2000 and 2026, supplemented by foundational documents issued earlier where they remain the basis of current practice, such as ATC-40 and FEMA 356. Search terms combined variations of "seismic vulnerability assessment," "existing buildings," "multistorey," "retrofitting," "rapid visual screening," "pushover analysis," "fragility curves," and "machine learning" to capture both the established analytical literature and the more recent data-driven strand of research.

Sources were included if they addressed vulnerability assessment methodology, retrofitting or strengthening technique performance, or case-study evidence specific to reinforced concrete, masonry, or mixed multistorey construction, and if they reported enough methodological detail to be classified against the framework used in this review. Sources focused exclusively on newly designed buildings, on non-seismic hazards, or on structural typologies with no bearing on multistorey construction, such as isolated bridge components, were excluded unless they contributed a fragility or damage-prediction methodology that had been generalized to buildings elsewhere in the literature. Each retained source was then classified along two axes: the assessment or intervention category

it addressed, spanning empirical screening, analytical or mechanics-based assessment, element-level retrofitting, system-level retrofitting, and data-driven prediction; and the geographic or code context it was developed for, since seismic zoning, construction practice, and enforcement culture vary enough between regions that findings do not always generalize directly.

The synthesis itself proceeded thematically rather than chronologically, grouping studies by method family so that competing approaches to the same underlying problem, for instance HAZUS-based fragility curves versus locally calibrated vulnerability indices, could be compared directly on the criteria of accuracy, data requirements, computational cost, and practical adoption. This approach necessarily involves a degree of interpretive judgment in how studies are grouped and compared, and it does not attempt to quantitatively pool results across studies using meta-analytic statistics such as effect sizes, since the underlying methods, building typologies, and reported metrics are too heterogeneous to combine numerically in a meaningful way.

4. CRITICAL ANALYSIS OF PAST WORK

Taken as a body, the vulnerability assessment literature shows a clear trade-off between speed and fidelity that no single method has fully resolved. RVS procedures are fast and inexpensive enough to apply across an entire city, which is precisely why they dominate large-scale risk mapping efforts in India, Bangladesh, and Pakistan [17], [18], but their qualitative scoring systems depend heavily on surveyor judgment, and several studies acknowledge that classification accuracy drops when buildings deviate from the archetypes the scoring system was calibrated against [19]. The structural-score refinement proposed for Indian RC frames is a genuine improvement in this respect, since it ties the RVS score back to pushover-derived collapse probability rather than leaving the mapping between score and risk implicit, but this calibration step itself depends on assumptions about typical reinforcement detailing and material strength that may not hold for informally constructed buildings, which are exactly the buildings most in need of accurate screening [19].

Analytical methods built on pushover analysis and fragility curves offer more defensible engineering justification but come with their own limitations that are sometimes understated in the literature. Fragility curves developed under HAZUS were calibrated primarily on United States building inventories, and studies that transplanted the methodology to Iran and other regions found systematic mismatches between predicted and observed damage, attributing the gap to differences in construction quality, material properties, and site conditions that the original HAZUS parameters do not capture [24]. This is a recurring critique across the reviewed literature: methods developed and validated in one seismic and construction context are frequently applied elsewhere with only partial recalibration, and the resulting vulnerability estimates should be read with more caution than they are sometimes given. Pushover analysis itself, while standard practice, rests on a static approximation of an inherently dynamic phenomenon, and several soft-storey studies note that the method's accuracy depends on the choice of lateral load distribution and drift threshold, choices that are not always made consistently across studies, complicating direct comparison of results [12], [20].

The retrofitting literature is comparatively strong on technique-specific performance data but weaker on system-level comparison. Individual studies of FRP wrapping, textile-reinforced mortar, jacketing, and base isolation

each report favourable results for their specific technique, and comparative reviews synthesizing across dozens of experimental programs generally confirm that FRP and TRM outperform conventional jacketing on strength-to-weight and disruption metrics [6], [8], [9]. However, relatively few studies directly compare element-level strengthening against system-level interventions such as base isolation on the same building under the same loading protocol; the controlled comparative test of RC jacketing, steel jacketing, and lead-rubber isolation is a notable exception, and its finding that isolation redirected damage away from the primary structure entirely, rather than merely delaying it, suggests that element-level strengthening and system-level isolation are not simply interchangeable options but represent different risk-management philosophies that the broader literature has not fully reconciled [11].

The emerging machine-learning literature is promising but still immature by the standards applied to the more established methods. Reported classification accuracies of eighty to ninety percent sound impressive, but the datasets underlying these models are often limited to a few hundred to a few thousand buildings from a specific region, such as the roughly three hundred-building dataset used for code-based vulnerability prediction in one study or the several-thousand-building masonry dataset compiled after the 2023 Türkiye earthquakes [26], [27]. Cross-regional generalization has barely been tested, and the reviewed studies rarely address what happens when a model trained on one country's building stock is applied to another's. This is the same generalization problem that affects HAZUS fragility curves, simply reappearing in a newer methodological wrapper, and it suggests that data-driven methods will need substantially larger and more geographically diverse training sets before they can be trusted for the same prioritization role that RVS currently occupies.

5. DISCUSSION

Reading across the assessment and retrofitting literature together, a coherent picture of best current practice emerges, even though no single reviewed study articulates it in full. Large-scale seismic risk reduction for multistorey building stock appears to require a tiered approach: inexpensive screening methods, whether traditional RVS or its machine-learning successors, to identify the highest-priority buildings across a large inventory, followed by mechanics-based analysis using pushover methods and fragility curves to characterize the specific vulnerability mechanisms present, and finally a retrofit selection process that weighs element-level techniques such as FRP jacketing against system-level interventions such as base isolation based on the severity and type of deficiency identified. The literature supports each stage individually far better than it supports the integration between stages; comparatively few studies trace a single building or building population all the way from screening through detailed assessment to a specific, cost-justified retrofit recommendation.

Regional disparity is a second theme that runs through nearly every category of work reviewed here. Codes such as Eurocode 8 Part 3, FEMA 356, and IS 1893 embody different philosophies for evaluating existing buildings, and studies developed under one framework do not always translate cleanly to another, a point reinforced by the repeated finding that HAZUS fragility parameters require local recalibration [17], [18], [24]. This has practical implications for developing countries with large stocks of informally constructed multistorey buildings, where the gap between available assessment tools and actual construction practice on the ground is often largest, precisely where the consequences of getting the assessment wrong are most severe.

A further point of tension concerns the balance between structural performance and practical deployability. FRP and TRM systems consistently outperform traditional jacketing on strength and disruption metrics in laboratory studies, yet adoption in the field, particularly in lower-income seismic regions, still leans heavily on conventional concrete and steel jacketing because of cost, availability of skilled labour, and familiarity among local contractors [9], [15]. This gap between what performs best in controlled testing and what gets built in practice is rarely addressed directly in the technical literature, which tends to report structural performance without engaging systematically with implementation economics or workforce capacity. Closing this gap, alongside expanding the geographic diversity of data-driven vulnerability models, appears to be one of the more consequential unresolved problems facing the field.

6. CONCLUSION

Seismic vulnerability in existing multistorey buildings is not the result of a single failure mode but of overlapping deficiencies in configuration, detailing, and material capacity that accumulated before modern seismic design became standard practice. This review has traced the evolution of assessment methodology from empirical rapid visual screening through mechanics-based pushover and fragility analysis to emerging machine-learning classification, alongside the parallel evolution of strengthening techniques from concrete jacketing to fibre-reinforced polymers, textile-reinforced mortar, and base isolation. The surveyed literature demonstrates real methodological progress on each front individually, but also reveals recurring limitations: assessment tools calibrated in one region transfer imperfectly to another, analytical methods depend on modelling choices that are not applied consistently across studies, retrofitting research remains fragmented by material and technique rather than integrated at the system level, and data-driven methods are still constrained by small, regionally narrow datasets. A tiered strategy that combines rapid screening for prioritization, detailed mechanics-based assessment for diagnosis, and technique selection informed by both structural performance and practical deployability offers the most defensible path forward. Future research would benefit from closing the gap between screening, assessment, and retrofit decision-making within single, well-documented case studies, and from building larger, more geographically diverse datasets to make data-driven vulnerability prediction genuinely transferable across regions and construction practices.

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