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Performance-Based Seismic Assessment and Retrofitting of Existing Reinforced Concrete Buildings

Abstract

Existing reinforced concrete (RC) buildings designed to older or substandard provisions can exhibit inadequate seismic performance because of poor reinforcement detailing, limited ductility, weak stories, and deficiencies in structural and nonstructural components. A reliable retrofit strategy therefore requires more than a check of individual members: it should quantify global structural capacity, identify the displacement and stiffness demands associated with an earthquake, and account for the consequences of damage and loss of functionality. This paper combines a displacement-based limit-displacement approach with a broader performance-based framework for evaluating seismic vulnerability, retrofit effectiveness, losses, and resilience. Instead of assessing individual structural components, we evaluate the entire building using a nonlinear static pushover analysis, to generate capacity curves and characterize the global response of existing structures. The assessment can then be extended through collapse fragility functions, component-level fragility and consequence functions, and recovery models. Two complementary retrofit philosophies are considered: global stiffening, including external shear walls, braces, or exoskeletons, and local strengthening of critical columns using steel, reinforced concrete, or engineered cementitious composite jackets. Together, these approaches provide a basis for selecting retrofit interventions according to structural demand, expected losses, resilience, and practical constraints.

Keywords: reinforced concrete; seismic retrofit; nonlinear pushover analysis; displacement-based assessment; fragility; resilience; vulnerability

1. Introduction

Recent destructive earthquakes have exposed the vulnerability of existing infrastructure, including non-code-conforming RC frame structures. Such buildings may be more vulnerable to structural failures than modern code-compliant structures because of poor structural and seismic detailing, and they often possess soft-story mechanism that makes them particularly susceptible to earthquake damage. Since these kinds of structures consist of a large portion of the existing infrastructure, particularly in earthquake-prone areas, effective assessment techniques are desirable to calculate the potential collapse and to compare various retrofit strategies for these existing structures. Although customary strength design methods can provide an expected level of life safety, substantial structural and nonstructural damage may still occur, generating direct and indirect losses through repair activities and downtime.

Traditional seismic assessment commonly proceeds through evaluation of member and joint capacities. This approach is based on an evaluation of the strength of structural elements and performance ratios. First, the critical elements are identified by an expert, based on engineering standards, and then, they are checked against the prescribed performance criteria. Finally, these critical elements are treated in the proposed seismic upgrade. However, local measures can only marginally affect the capacity and stiffness of the whole building, and this approach often leads to disproportionate levels of retrofit demand that greatly exceed the requirements of the current seismic provisions. In general, the assessment of individual components is more time-intensive and it does not provide the quantified assessment of retrofit needs. A complementary displacement-based model instead treats the structure as a whole object. Such an approach permits quantitative assessment of earthquake resistance and of the level of retrofit required.

The distinction is important because deficiencies in older RC buildings may be governed by lack of ductility rather than lack of strength. Corrosion of reinforcement, inadequate concrete cover, joint problems, and weak or flexible stories can further complicate assessment. High uncertainty in the actual condition of existing structures also makes it difficult to determine an appropriate retrofit level solely from component checks.

A performance-based perspective broadens the objective. Both structural elements (SEs) and nonstructural elements (NSEs) contribute to the functionality of a building. NSEs can be broadly classified as acceleration-sensitive and drift-sensitive; partition and curtain walls, for example, are sensitive to interstory drift, whereas sprinklers, HVAC systems, and ceilings are more vulnerable to floor acceleration. Consequently, a useful retrofit assessment should consider not only whether collapse is avoided, but also the economic, social, and environmental consequences of damage and the time required to restore functionality.

2. Global Seismic Assessment

The proposed integrated assessment begins with nonlinear static pushover analysis (NSPA). In this procedure, increasing lateral loads are applied to the structural model and the resulting base shear and displacement response are recorded. The resulting load-displacement or capacity curve provides a compact description of initial stiffness, strength, ductility, and ultimate response. Nonlinear static pushover analysis is widely used because it provides an efficient means of capacity assessment and performance-based safety checking.

Displacement-based assessment has particular advantages for existing structures because it accounts for the ductility of the system. Common approaches include the Capacity Spectrum Method (CSM) and the Displacement Coefficient Method (DCM). The CSM uses the interaction of demand and capacity spectra to identify a performance point, whereas the DCM estimates a target displacement from the spectral response of an elastic system and coefficients related to the effective fundamental period. However, these approaches have limited applicability to structures with low ductility. When a performance point cannot be established, the absence of such a point indicates a deficiency in earthquake resistance but does not by itself provide a direct quantitative measure of the retrofit demand.

The limit-displacement approach addresses this limitation by defining a safety target displacement (STD), representing the maximum displacement that the structure can attain during an earthquake without reaching failure. Earthquake resistance is defined as a ratio between the energy the structure can absorb at its current state and the energy it would be able to absorb at an ideal upgraded state. These energies can be estimated using capacity curves obtained through NSPA.

A target ductility curve (TDC) can then be developed to represent the ideal capacity curve of the assessed structure. The curve is bounded by the existing capacity curve and an elastic equilibrium curve representing a non-ductile structure. Two points are central to its construction: the yield point, associated with the development of the first plastic hinge and the peak base shear force, and the safety target displacement. The energy balance provides a means of relating the existing structure to the idealized ductile response and, consequently, of defining the additional stiffness required to maintain the displacement limits.

An important implication is that seismic demand can be expressed as additional stiffness rather than as a list of individual deficient members. The proposed procedure therefore allows a building to be evaluated as a whole and permits retrofit demand to be compared across different existing structures and seismic conditions.

3. Retrofit Strategies

Retrofit measures can broadly be divided into local interventions and global interventions. Local treatment includes jacketing of existing RC members using concrete, steel, or composite materials. These techniques improve the load-bearing capacity and ductility of critical structural elements. Global measures, in contrast, aim to enhance lateral resistance or reduce seismic demand through systems such as bracing, cables, steel exoskeletons, shear walls, infill walls, base isolation, and energy dissipation devices.

External stiffening is particularly attractive where the objective is to increase global stiffness without strengthening every deficient component. External shear walls can be proportioned according to the estimated demand, and similar principles can be applied to exoskeletons or external braces. Shear walls have been shown to be efficient in controlling lateral drifts and reducing damage to frame members. Their principal drawback is that the existing foundation system may require strengthening to resist increased overturning moments and the additional weight of the structure. Nevertheless, external upgrading can offer lower installation costs than local repairs, avoid shutting down the building, and rely on conventional construction materials.

Local column strengthening provides another route, particularly where structural behavior is governed by column capacities and story response. Four representative alternatives are steel plate jacketing (SPJ), steel angle jacketing (SAJ), reinforced concrete jacketing (RCJ), and engineered cementitious composite jacketing (ECCJ). These interventions alter the lateral force-resisting system locally while increasing column capacity and improving the global response.

4. Performance-Based Loss and Resilience Assessment

Structural capacity alone does not capture the complete consequences of an earthquake. A performance-based framework can connect the global response of the building to component damage and, subsequently, to direct and indirect losses. Capacity curves obtained from NSP can be used to determine the effectiveness of retrofit strategies, while collapse fragility functions provide a probabilistic representation of collapse vulnerability.

At the component level, fragility curves describe the probability of exceeding specified damage states, while consequence functions translate those damage states into economic, social, and environmental consequences. Engineering demand parameters such as interstory drift and peak floor acceleration provide the link between structural response and component damage. The resulting direct losses may include repair costs, casualties, fatalities, property damage, and environmental impacts. Indirect losses arise when the building cannot perform its intended function and include downtime, repair-related delays, and business or service interruption.

Resilience is therefore associated with the recovery of functionality. A recovery function can be constructed using repair times, the repair sequence, obstructing delays, and utility accessibility. This perspective is especially important for critical facilities such as hospitals, where the objective of retrofit extends beyond collapse prevention to maintaining or rapidly restoring essential services. The performance-based framework explicitly considers recovery of functionality and associated indirect losses.

5. Integrated Retrofit Decision-Making

The two assessment approaches address different but closely related aspects of seismic retrofit. The limit-displacement method focuses on quantifying the structural modifications required to achieve a desired level of earthquake resistance by estimating the additional stiffness needed to satisfy prescribed displacement limits. In contrast, the performance-based framework evaluates the broader implications of retrofit by examining its influence on structural performance, damage, direct and indirect losses, and post-earthquake functionality. Together, these approaches provide a more comprehensive basis for selecting retrofit strategies, combining an estimate of structural demand with an assessment of their effectiveness in reducing vulnerability and improving resilience.

An integrated assessment may therefore be carried out through a sequence of analytical steps. The existing building is first analyzed using nonlinear static pushover analysis (NSPA) to establish its capacity curve. The resulting force-displacement relationship is then used to determine the displacement limits and seismic resistance factor, particularly for structures where conventional displacement-based procedures such as the Capacity Spectrum Method (CSM) or Displacement Coefficient Method (DCM) are not applicable because of limited ductility. Candidate retrofit schemes, whether based on global stiffening or local strengthening, are subsequently evaluated by comparing their modified capacity curves with that of the original structure. Finally, fragility relationships are used to estimate expected damage at different seismic hazard levels, and the resulting structural response is translated into direct losses, indirect losses, and resilience measures that can be combined using normalized performance indices and stakeholder-defined weighting factors to support retrofit decision-making.

Results from a five-story hospital case study illustrate the potential of this approach. Retrofitting only the ground-floor columns using SPJ, SAJ, RCJ, and ECJ alternatives enhanced lateral load and deformation capacity in both principal directions. The reported assessment found that retrofitting reduced the probability of collapse as well as economic, social, and environmental losses, while repair times were also reduced, increasing seismic resilience. Under the limitations of that study, SPJ-3 was identified as the most effective alternative, followed by other jacketing strategies. Importantly, this conclusion depended on the factors and weightings included in the decision framework and should not be interpreted as a universal ranking of retrofit technologies.

6. Discussion

An integrated approach highlights several limitations of conventional assessment. A building that satisfies a member-level strength requirement may nevertheless experience substantial nonstructural damage and prolonged downtime. Conversely, a global retrofit may improve the overall force-displacement response without directly correcting every local deficiency. The appropriate strategy therefore depends on the mechanism governing building behavior, the desired performance level, the available construction options, and the consequences of failure.

The limit-displacement method is especially useful for low-ductility existing buildings because commonly accepted displacement-based procedures may fail to establish a meaningful performance point. By treating the building as a whole and using energy balance, the method produces a resistance factor and a corresponding stiffness demand. This creates a common quantitative basis for comparing buildings and retrofit scenarios. The method has been demonstrated for a low-ductility structure that could not be adequately analyzed using conventional DCM and CSM procedures.

At the same time, performance-based loss assessment makes the decision more transparent to owners and stakeholders. Direct and indirect consequences can be expressed in economic, social, and environmental terms, and resilience can be incorporated through recovery of functionality. Such an approach is particularly relevant when retrofit decisions involve competing priorities, such as minimizing initial intervention while preserving post-earthquake operation.

Both frameworks also depend on modeling assumptions. Infill walls, foundations, material uncertainty, retrofit cost, maintenance requirements, and other practical factors can substantially influence the final decision. Consequently, calculated retrofit rankings should be interpreted within the scope of the assumptions used.

7. Conclusions

Existing RC buildings require assessment methods that quantify both structural deficiency and the consequences of earthquake damage. Nonlinear static pushover analysis provides an efficient means of obtaining global capacity curves, but low-ductility structures may not be adequately assessed using conventional CSM or DCM procedures. A limit-displacement approach addresses this problem by defining a safety target displacement and an ideal capacity state through energy balance. The resulting resistance factor expresses the relationship between the energy absorbed by the existing structure and that available in the ideal upgraded state, while the additional stiffness required to reach the target defines the seismic demand.

Performance-based loss assessment complements this structural measure by incorporating structural and nonstructural damage, collapse fragility, direct losses, indirect losses, and recovery of functionality. Local jacketing and global stiffening represent complementary retrofit strategies: the former targets critical components, whereas the latter modifies the global lateral response.

The combined framework provides a rational basis for comparing retrofit alternatives according to structural performance, seismic risk, economic and social consequences, and resilience. It also supports more informed decisions about whether the most appropriate intervention is local strengthening, external stiffening, or another system-level measure. Future applications should incorporate the effects of infill walls and bracing systems, different foundation conditions, retrofit and maintenance costs, and a wider range of building heights and configurations. The need for such extensions is also identified in the limit-displacement study, which recommends further investigation of infill walls, bracing systems, foundation types, and medium-rise buildings.

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