

A Critical Review on Strength Enhancement of Existing Structure

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Abstract—Structural strengthening is an essential technique used to enhance the load-carrying capacity, durability, and seismic performance of existing structures. Many buildings and infrastructure systems deteriorate over time due to aging, environmental effects, increased loading, design deficiencies, or changes in functional requirements. Structural strengthening methods are therefore implemented to improve the safety, stability, and service life of such structures without complete demolition and reconstruction. Various strengthening techniques such as reinforced concrete jacketing, steel plate bonding, fiber reinforced polymer (FRP) wrapping, external prestressing, and the addition of shear walls or bracing systems are widely used in structural engineering practice. Analytical tools such as pushover analysis and nonlinear structural evaluation are often used to assess the performance of structures before and after strengthening.

Index Terms—Structural strengthening, Retrofitting, Push Over Analysis.

I. INTRODUCTION

The effects of earthquakes on structures can be devastating and sometimes catastrophic. Structures need to be built to withstand seismic activity to mitigate the impacts of such events. The underlying cause of structures collapsing due to earthquakes often has to do with design, construction, and maintenance. In this article, we discuss the main causes of structural collapse during an earthquake and provide insights for civil engineers on how to design and construct structures that are resilient to seismic activity. One of the main causes of structural collapse during earthquakes is poor design. For instance, buildings that are not designed to withstand the lateral forces exerted by an earthquake

can easily collapse. In addition, buildings that are not properly reinforced are also susceptible to collapse. In many cases, the use of sub-standard materials and construction methods can also contribute to the collapse of a structure during an earthquake. Another cause of the collapse is poor construction. This can happen when buildings are not constructed according to their designed plans. For example, if the foundation of a building is not properly dug or if the building is not properly reinforced, it is more likely to collapse during an earthquake. Retrofitting is the method of treatment of a structure to increase its usable life. The retrofitting may include a number of procedures depending upon the structure, degree of damage, purpose of retrofit, etc. Before moving ahead let us understand why structures fail. Structures are sometimes subjected to loads for which they were originally not designed. These loads may occur due to earthquakes (seismic load), changes in loading patterns, etc. Hence, the structure experiences extraordinary stress and fails under it.

II. CORRESPONDING LITERATURE

Hassan and Yasin (2015) investigated the seismic performance of reinforced concrete buildings using nonlinear static pushover analysis. Their study focused on evaluating the behavior of reinforced concrete structures subjected to increasing lateral seismic forces. The authors used pushover analysis to develop capacity curves representing the relationship between base shear and roof displacement. The analysis also helped identify the formation of plastic hinges in beams and columns and determine the critical structural components likely to experience damage during severe earthquakes. Their findings indicated

that pushover analysis is a useful method for assessing the strength, stiffness, ductility, and deformation capacity of existing reinforced concrete buildings. The study emphasized that nonlinear analysis can provide valuable information for identifying structural deficiencies and selecting appropriate seismic strengthening measures.

The seismic behavior of reinforced concrete buildings with particular emphasis on soft storey conditions is studied by Rathod and Ishtiyaque (2016). The authors compared different structural configurations and evaluated their behavior using pushover analysis. The study showed that masonry infill can increase the lateral stiffness and strength of a building, whereas soft-storey configurations can result in significant concentration of seismic demand and lateral deformation. Parameters such as base shear, roof displacement, storey drift, and plastic-hinge formation were considered to evaluate structural performance. The authors concluded that soft-storey buildings require careful seismic assessment and may require strengthening measures to improve their lateral load-resisting capacity.

Talahmeh *et al.* (2014) investigated seismic strengthening techniques for reinforced concrete structures using CFRP and concrete jacketing. Their study demonstrated that both conventional and advanced strengthening techniques can improve the seismic performance of existing reinforced concrete structures. Concrete jacketing can increase the cross-sectional capacity, stiffness, and confinement of structural members, while CFRP strengthening provides significant strength enhancement with relatively little additional structural weight. The authors highlighted the advantages of CFRP materials, including their high strength to weight ratio and resistance to corrosion. The study concluded that the selection of a strengthening technique should depend on the structural deficiency, required performance level, existing material condition, and construction requirements.

Griffith and Pinto (2002) examined the seismic behavior of masonry-infilled reinforced concrete frames. Their study highlighted the important contribution of masonry infill walls to the lateral stiffness and strength of reinforced concrete frames. Although infill walls can significantly increase the

initial stiffness of a building, their behavior changes as seismic deformation increases because cracking and degradation occur under lateral loading. The study demonstrated that ignoring masonry infill in structural analysis may lead to inaccurate predictions of structural response. The authors emphasized that the distribution and behavior of infill walls should be properly considered during seismic assessment, particularly in existing buildings where irregular infill arrangements may produce undesirable stiffness distributions.

Lakshmanan *et al* (2008) investigated the behavior of reinforced concrete beam-column joints under seismic loading. The study emphasized that beam-column joints are among the most critical components of reinforced concrete frames because inadequate reinforcement detailing and insufficient confinement can result in brittle failure during earthquakes. Strengthening and repair of deficient joints can improve their strength, stiffness, and deformation capacity. The study also highlighted the importance of evaluating the existing condition of beam-column joints before selecting an appropriate retrofit method. The findings indicate that strengthening should address the actual failure mechanism of the joint rather than simply increasing the strength of adjacent beams or columns.

Mukherjee and Kalyani *et al* (2002) investigated the application of fiber reinforced polymer composites for seismic strengthening of reinforced concrete structures. Their study demonstrated that FRP materials can significantly improve the strength and ductility of reinforced concrete structural members. One of the major advantages of FRP strengthening is its high strength to weight ratio, which allows structural capacity to be increased without significantly increasing the dead load of the building. The authors also highlighted the corrosion resistance and relatively simple installation of FRP systems compared with some conventional strengthening methods. Their findings support the application of FRP composites for strengthening beams, columns, and other deficient structural elements.

Agrawal and Chourasia (2014) evaluated the seismic performance of reinforced concrete buildings using nonlinear pushover analysis. Their study compared the

structural response of buildings under increasing lateral loads and examined parameters such as base shear, roof displacement, and plastic hinge development. The research demonstrated that nonlinear static analysis can provide useful information regarding the expected progression of structural damage and the available deformation capacity. The authors also highlighted the importance of comparing the performance of structures before and after strengthening. Their findings indicate that appropriate retrofit measures can improve both the load carrying capacity and deformation capacity of reinforced concrete buildings.

Martellotta *et al.* (2013) investigated the effect of different bracing systems on the seismic behavior of reinforced concrete frame structures. Their study considered different bracing configurations and evaluated their influence on lateral stiffness, strength, displacement, and storey drift. The addition of bracing systems was found to improve the lateral load resisting capacity of reinforced concrete frames and reduce seismic deformation.

The research demonstrated that the configuration and location of bracing are important factors in determining structural performance. The authors concluded that properly designed bracing systems can be effectively used for strengthening existing buildings, particularly when inadequate lateral stiffness or strength is identified as a major structural deficiency.

Patel *et al.* (2013) reviewed different seismic retrofitting techniques applicable to reinforced concrete buildings. The study considered techniques such as reinforced concrete jacketing, steel jacketing, FRP wrapping, bracing, and other strengthening methods. The author emphasized that each retrofit technique has specific advantages and limitations and that the selection of an appropriate method should be based on the structural condition, type of deficiency, seismic demand, and required performance. Concrete and steel jacketing can provide significant increases in member strength and stiffness, whereas FRP systems can provide strengthening with relatively low additional weight. The study concluded that systematic seismic retrofitting can significantly improve the safety and resilience of existing reinforced concrete buildings.

Rai *et al.* (2005) discussed the seismic evaluation and strengthening of existing buildings, with particular emphasis on buildings that may not satisfy modern seismic design requirements. The study highlighted the importance of identifying structural deficiencies before selecting a strengthening technique. Potential interventions include concrete and steel jacketing, addition of shear walls, steel bracing, FRP strengthening, and other structural modifications. Rai emphasized that strengthening should consider both local deficiencies, such as inadequate columns or beam column joints, and global deficiencies, such as insufficient lateral resistance or excessive storey drift. The study supports a systematic approach involving condition assessment, seismic analysis, identification of deficiencies, selection of retrofit measures, and verification of the strengthened structure.

Dyavanal and Vasanwala *et al.* (2014) investigated nonlinear static pushover analysis of multi-storey reinforced concrete buildings. Their study focused on the nonlinear response of structures subjected to increasing lateral loads and the development of capacity curves. Plastic hinge formation in structural members was used to identify potential failure mechanisms and critical components. The authors demonstrated that pushover analysis can provide valuable information about structural capacity, ductility, deformation, and performance levels. They also emphasized that nonlinear analysis provides a better understanding of structural behavior beyond the elastic range compared with conventional linear analysis. Their study supports the use of pushover analysis as an important tool for seismic evaluation and retrofit assessment.

Krawinkler and Seneviratna (1998) critically examined the advantages and limitations of pushover analysis for seismic performance evaluation. Their study demonstrated that pushover analysis can provide useful information regarding structural capacity, nonlinear response, plastic hinge development, and displacement demand. However, the authors also identified important limitations associated with the use of predefined lateral load patterns. Pushover analysis may not fully represent higher-mode effects, dynamic characteristics, torsional behavior, and complex nonlinear response in certain structures. Therefore, the authors emphasized that pushover analysis should be

applied carefully and that its assumptions and limitations should be considered when interpreting the results. Their work remains particularly relevant to the assessment of existing structures and the selection of appropriate analytical procedures.

Fardis *et al* (2009) discussed seismic design, assessment, and retrofitting of concrete buildings. His work emphasized the vulnerability of existing reinforced concrete buildings that were designed before the introduction of modern seismic design provisions. Common deficiencies include inadequate ductility, insufficient confinement reinforcement, poor detailing of beam column joints, and inadequate lateral resistance. Fardis discussed various strengthening measures, including jacketing, strengthening of structural members, addition of structural walls, and other retrofit techniques. The study emphasized that both local and global structural deficiencies should be considered during seismic assessment. The work also highlights the importance of compatibility between the existing structure and the proposed strengthening system.

Paulay and Priestley (1992) established fundamental principles for seismic design of reinforced concrete and masonry buildings. Their work emphasized that seismic-resistant structures should possess adequate ductility and deformation capacity in addition to sufficient strength. They discussed important principles such as capacity design, confinement reinforcement, appropriate detailing, energy dissipation, and the strong column weak beam concept. These principles are highly relevant to structural strengthening because increasing the strength of a member alone does not necessarily guarantee improved seismic performance. Strengthening should promote a desirable failure mechanism and prevent sudden brittle failure. Their work has therefore provided a fundamental basis for modern seismic design and retrofit practices.

The Applied Technology Council (1996), through ATC-40: Seismic Evaluation and Retrofit of Concrete Buildings, established an important framework for performance-based seismic evaluation and strengthening. The guideline provides procedures for evaluating existing concrete buildings, identifying structural deficiencies, establishing performance objectives, and selecting appropriate retrofit measures.

ATC-40 also introduced the capacity spectrum approach for comparing structural capacity with seismic demand. The guideline emphasizes performance objectives such as Immediate Occupancy, Life Safety, and Collapse Prevention. It provides an important framework for applying nonlinear static analysis to existing buildings and determining whether strengthening is required.

The Federal Emergency Management Agency (FEMA, 2000), through FEMA-356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings, provided procedures for seismic evaluation and rehabilitation of existing buildings. The document emphasizes the assessment of structural components, identification of deficiencies, establishment of performance objectives, and selection of suitable rehabilitation measures. FEMA-356 recognizes that structural performance should be evaluated in terms of both strength and deformation capacity. The guideline also provides criteria for evaluating beams, columns, walls, connections, and other structural components. It therefore provides a systematic framework for determining the need for strengthening and evaluating the expected performance of rehabilitated structures.

The European Committee for Standardization (2004), through Eurocode 8, established provisions for earthquake-resistant design and seismic assessment of structures. The standard emphasizes adequate strength, stiffness, ductility, regularity, and energy dissipation. Its provisions concerning existing structures provide a framework for assessing structural deficiencies and selecting appropriate strengthening measures. Eurocode 8 recognizes that irregularity in stiffness, mass, and structural configuration can significantly influence seismic response. Therefore, seismic assessment and retrofit design should consider the overall behavior of the structural system rather than focusing only on individual members.

Agarwal and Shrikhande (2006) discussed the principles of earthquake-resistant structural design and seismic analysis. Their work covers seismic forces, structural dynamics, response spectrum analysis, structural configuration, and earthquake-resistant detailing. The authors emphasized that the dynamic characteristics of a building, including natural period, mode shapes, damping, mass distribution, and stiffness distribution, significantly influence its seismic response. Their work highlights the

importance of selecting an appropriate analytical procedure according to the complexity and characteristics of the structure. They also emphasized the role of regular structural configuration and adequate detailing in reducing earthquake-induced damage.

Duggal (2010) discussed the fundamental principles of earthquake-resistant design, including seismic loading, structural dynamics, ductility, structural configuration, and detailing. The author emphasized that structures should possess sufficient strength, stiffness, ductility, and energy-dissipation capacity to withstand earthquake forces. Particular attention was given to the importance of regular structural configuration and reliable connections between structural members. Duggal also emphasized the importance of construction quality because inadequate workmanship, poor materials, insufficient reinforcement, and improper detailing can significantly reduce the actual performance of a structure. These considerations are especially important when assessing older existing buildings.

The Bureau of Indian Standards (2016) published IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures, which provides provisions for seismic design and analysis of buildings in India. The standard establishes requirements for determining seismic forces and provides guidance concerning structural configuration, seismic zones, design forces, and analysis procedures. It emphasizes the importance of adequate strength, stiffness, and ductility for earthquake-resistant structures. IS 1893 is particularly relevant to the assessment and strengthening of existing structures in India because it provides the current seismic design framework against which structural performance can be evaluated.

III. SUMMARY OF REVIEWED LITERATURE

The reviewed literature demonstrates that the strengthening of existing structures has developed from conventional member-strengthening techniques toward an integrated performance-based approach. Paulay and Priestley (1992) emphasized ductility, capacity design, and controlled energy dissipation, establishing fundamental principles for seismic-resistant reinforced concrete structures. Applied Technology Council (1996) and Federal Emergency

Management Agency (2000) subsequently provided systematic frameworks for evaluating and rehabilitating existing buildings using performance-based approaches.

The development and application of nonlinear static analysis were further examined by Krawinkler and Seneviratna (1998), while Hassan and Yasin (2015) and Dyavanal and Vasanwala (2014) demonstrated the application of pushover analysis to reinforced concrete buildings. These studies indicate that pushover analysis can provide valuable information about base shear, roof displacement, plastic-hinge formation, ductility, and structural capacity.

Research on strengthening techniques shows that different interventions are appropriate for different structural deficiencies. Mukherjee and Kalyani (2002) and Talahmeh et al. (2014) highlighted the effectiveness of FRP and CFRP systems, while Patel (2013) and Rai (2005) discussed a broader range of retrofit techniques. Martellotta et al. (2013) demonstrated the potential of bracing systems for improving lateral stiffness and strength. Lakshmanan (2008) emphasized the importance of strengthening vulnerable beam-column joints.

The literature also demonstrates the importance of considering non-structural and secondary structural components. Griffith and Pinto (2002) showed that masonry infill can significantly influence the stiffness and strength of reinforced concrete frames. Rathod and Ishtiyaque (2016) highlighted the vulnerability associated with soft-storey configurations. These findings indicate that seismic assessment must consider the actual configuration and behavior of an existing building rather than relying exclusively on simplified structural models.

In the Indian context, Agarwal and Shrikhande (2006), Duggal (2010), Rai (2005), and Bureau of Indian Standards (2016) provide important guidance regarding earthquake-resistant design, seismic evaluation, and structural safety. Their work highlights the importance of structural configuration, ductility, appropriate analysis, construction quality, and compliance with seismic provisions.

Overall, the literature establishes that effective strengthening requires a systematic assessment of the existing structure followed by identification of deficiencies, selection of an appropriate strengthening technique, nonlinear structural analysis, and

verification of post-strengthening performance. The success of a retrofit cannot be assessed solely by an increase in base shear; improvements in stiffness, ductility, deformation capacity, storey drift, energy dissipation, failure mechanism, durability, constructability, and long-term performance must also be considered.

IV. CONCLUSION

The critical review of existing research demonstrates that structural strengthening and seismic retrofitting are essential for improving the safety, serviceability, and durability of existing buildings. Existing structures may become vulnerable due to aging, deterioration, inadequate original design, poor construction practices, changes in building use, increased loading, or insufficient consideration of seismic forces.

Therefore, systematic assessment and appropriate strengthening measures are necessary to extend the service life of structures and reduce the risk of severe damage or collapse during earthquakes.

The reviewed studies indicate that strengthening techniques such as reinforced concrete jacketing, steel jacketing and plate bonding, fiber-reinforced polymer (FRP) wrapping, external strengthening, shear-wall addition, and steel bracing can substantially improve the strength, stiffness, ductility, and deformation capacity of existing structures.

However, the effectiveness of any particular technique depends on the structural deficiencies, building configuration, material condition, construction feasibility, and desired performance objectives. Consequently, strengthening should be selected only after a detailed assessment of the existing structure rather than applying a single method universally.

The literature also establishes the importance of nonlinear analytical methods, particularly pushover analysis, in evaluating the seismic performance of existing and strengthened structures. Pushover analysis provides useful information regarding base shear capacity, roof displacement, storey drift, plastic hinge formation, ductility, and performance levels. It therefore enables engineers to identify critical structural components and compare the structural capacity before and after strengthening. Nevertheless, pushover analysis is an approximation of the actual dynamic response and its limitations should be

recognized, particularly for highly irregular structures and cases where higher-mode effects are significant.

The reviewed standards and guidelines, including ATC-40, FEMA-356, Eurocode 8, and IS 1893, emphasize performance-based evaluation, adequate strength and stiffness, ductile detailing, and reliable load paths. These principles demonstrate that seismic strengthening should address both local deficiencies, such as inadequate beam column joints or column confinement, and global deficiencies, such as soft-storey behavior, excessive drift, or insufficient lateral resistance.

Overall, the literature confirms that structural strengthening is a technically effective approach for enhancing the seismic resilience of existing structures while avoiding complete demolition and reconstruction. A reliable strengthening strategy should follow a systematic process consisting of condition assessment, identification of structural deficiencies, and selection of suitable strengthening techniques, analytical evaluation, implementation, and post strengthening verification. Future research should focus on integrating advanced materials, performance-based assessment, nonlinear analysis, sustainability considerations, and cost-effective strengthening methods to develop safer and more resilient existing structures.

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