IMPROVING SEISMIC RESILIENCE OF EXISTING RC STRUCTURES

IVAN RACHOV*, MARINA TRAYKOVA

University of Architecture, Civil Engineering and Geodesy (UACEG),
Faculty of Civil Engineering, Department of 'Reinforced Concrete Structures',
1 Hr. Smirnenski Blvrd, 1146 Sofia, Bulgaria,
e-mails: ivan.rachov33@gmail.com, marina521961@gmail.com

Abstract. Recent seismic events, e.g., the 2023 Turkey and Syria earthquakes, have brought forward the necessity for improving the resilience of existing RC structures. These events have shifted the emphasis from Performance-Based Design (PBD) to Resilience-Based Design (RBD) to maintain functionality and limit damages caused by natural or man-made hazards. Resilient designs emphasize robustness, adaptability, and swift recovery, enabling structures to withstand disruptions and quickly restore functionality. Retrofitting, preventive and essential maintenance, and innovative strategies like ensuring sufficient deformation capacity, alternate load paths, and compartmentalization enhance resilience. Concrete materials, known for durability and hazard resistance, play a pivotal role in resilient construction. Several measures for improving the resilience of existing RC structures by retrofitting are discussed in this paper.

Keywords: resilience, seismic retrofitting, robustness, existing RC structures

1. INTRODUCTION

The reliability of structures is affected by various impacts that generally have a negative effect, from extreme weather conditions, due to climate change, to natural or man-made hazards [1].

Over the past few decades, there has been an exponential increase in human and material losses from disaster events. While the green building movement has traditionally focused on the environmental aspects of buildings, communities must now address the need for resilience while rebuilding to meet the challenge of the next natural disaster [2].

Instantaneous deterioration may cause a sudden shock to the structures and often results in performance reductions in a relatively short time [3]. It is induced by extreme events and is classified into two major categories, herein including (1) natural

* Corresponding author
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hazards such as earthquakes, tsunamis, storms, flooding, landslides, wildfire, and volcanic activity, among others, and (2) man-made disasters such as terrorist attacks or blasts due to exploding gas cylinders, fires due to gas leakage or short circuit, among others. These deterioration mechanisms can reduce the structural performance or increase the probability of the failure of structural members, or may trigger complete structural failure modes, including progressive collapse or complete collapse, among others [4,5]. Moreover, this may shorten the service life of a structure and could cause significant social disruptions and economic consequences [6].

Recent natural disasters and climate change-induced extremes emphasize the urgent need to enhance the overall resilience of society by addressing the various hazards that buildings may face. Current design approaches recognize the need for integrated risk assessments, but studies primarily focus on existing RC buildings and single hazards, neglecting the impact of multiple hazards and resilience quantifications. However, it is crucial to consider multi-hazard scenarios and quantify economic, environmental, and resilience losses to pursue effective solutions from the early-stage design of both new buildings and retrofitting interventions [7].

One of the ways to improve seismic resilience and reduce damage is retrofitting. Retrofitting techniques encompass a range of methodologies aimed at upgrading existing RC structures to withstand seismic forces. These techniques are designed to enhance the overall structural performance of buildings by improving load-bearing capacities, ductility, and energy dissipation characteristics [8]. Key elements of retrofitting include the addition of supplemental structural elements, modification of existing RC structural elements, and the application of advanced materials to enhance seismic resistance [9].

2. ROBUSTNESS AS A CHARACTERISTIC OF RESILIENT STRUCTURES

Attributes defining resilience are robustness, redundancy, resourcefulness, and rapidity (Bruneau et al. 2003), meaning that, as robustness is an attribute of resilience, it can have a direct implication on the reduction of the structure's performance [1].

One of the major concepts that plays a critical role in improving seismic resilience is robustness. In earthquake engineering, seismic robustness is defined as the prevention of collapse against strong earthquakes [10].

In common sense, the word "robust" is used in the context of being insensitive or stable. It is assumed that small causes do not produce a large effect on robust persons or things. If this context is applied to construction, society expects robust structures whose damage or failure is limited to an extent that is in reasonable proportion to the cause. This means, for example, that local damage must not lead to failure of the entire structure. If this understanding is transferred to large buildings, they can only be considered robust if the failure of a load-bearing element does not lead to the collapse of the complete building. In this context, columns are the most critical load-bearing elements in building construction. They carry high loads and, due to their slenderness, are particularly vulnerable to impacts such as collision or explosion. Therefore, it is sensible to design large buildings also for the possible failure of a column [11].

The final step towards disaster resilience is to build with robust building materials. Some of the qualities of robust building materials include versatility, strength, wind and water resistance, seismic resistance, fire resistance, energy efficiency, and durability. Concrete building systems are especially suited to provide resistance to natural hazards. Concrete has the necessary hardness and mass to resist the high winds and flying debris of tornadoes and hurricanes. Concrete is fire-resistant and non-flammable, which means it can contain fires and will not contribute to the spreading of fire. Reinforced concrete framing systems can be designed to resist the most severe earthquakes without collapse. Concrete doesn’t rot or rust even if it is subject to flooding [2].

3. RESILIENCE OF EXISTING RC STRUCTURES

Let be a time-variant functionality indicator in the range [0;1], with for undamaged systems and for fully damaged systems. The occurrence of an extreme event at a time may cause a sudden loss of system functionality. As shown in Fig. 1, the loss ΔQ can be totally or partially recovered by post-event restoration activities over a recovery time interval, where and are the initial and final times of the restoration process, respectively, and is the idle time or the elapsed time between the occurrence of the extreme event and the beginning of the recovery process.

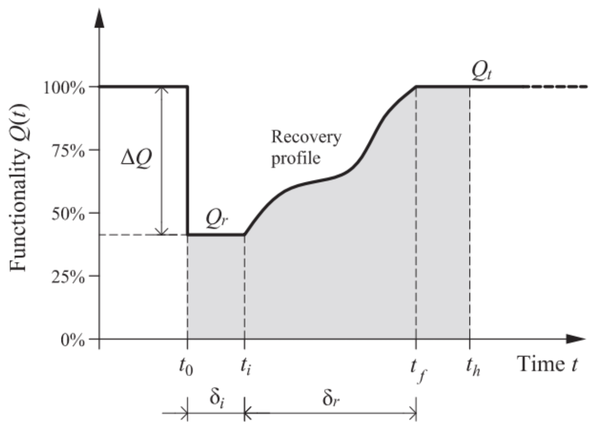

Fig. 1. System functionality and definition of resilience [12].

Resilience can be defined as the capability of the system to sustain the effects of the extreme event at a time and to recover efficiently to a target level of functionality at a time. Based on this definition, an effective dimensionless measure of resilience is given by an average value of the post-event functionality over a time horizon [12,13,14]:

$$R = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} Q(t)dt \; [17] \tag{1}$$

This concept is shown in Fig. 1, where resilience is associated with the area underlying the functionality profile over the time interval. The practical applicability of this qualitative and quantitative definition of resilience has been shown in literature for existing RC structures and real infrastructure networks [12,14,15,16,17].

There are many definitions and concepts of resilience of building structures and component connections. What all these different concepts have in common, however, is that resilience is the ability or capacity of a system to maintain its functionality, or at least to regain it in the short term, even while facing unusual or unexpected stress situations. Resilience can refer to natural as well as to technical systems. [18].

The resilience of a structure is to determine by how susceptible to damage or how resistant this structure is when exposed to a natural event. It is largely determined by object characteristics, for example, the construction method, materials used, protective devices, etc. The risk can be reduced by improving the resistance of a structure to the effects of these natural hazards by regular maintenance (servicing, condition assessment, refurbishment), and by protective and damage mitigation measures before, during, and after the event [11], such as retrofitting, etc.

In recent years, more and more scholars have begun to transition from Performance-Based Design (PBD) to Resilience-Based Design (RBD). While Performance-Based Design effectively minimizes the risk of loss of life during seismic events, it does not adequately address the need to maintain functionality or limit structural damage. In contrast, the emerging Resilience-Based Earthquake Design offers a promising approach to meet these additional demands. The main objective of Resilience-Based Design (RBD) is to make communities 'resilient'. It aims to develop actions and technologies that allow the structure and/or community to recover its function as promptly as possible whenever a disaster occurs (Cimellaro, 2013) [19].

Disaster mitigation works and is cost-effective. Spending time and money up front to reduce the likelihood of loss during a natural disaster can bring significant benefits to building owners and communities, including lower insurance costs, higher property values, security to residents, maintaining a consistent tax base, and minimizing the cost of disaster response and recovery [2].

Reinforced concrete is the most common and versatile construction system used for buildings and structures worldwide. Ensuring these assets are resilient enough to survive extreme loads and can be maintained and preserved for future generations to use without the need for demolition and replacement inherently improves the sustainability of our built environment [20].

4. REVIEW OF RETROFITTING TECHNIQUES FOR RC STRUCTURES

The term 'retrofitting' is mainly used in the context of the strengthening of weak buildings to make them strong enough to withstand seismic forces through various repairing methods. The main purpose of retrofitting is to structurally treat the buildings with an aim to restore 70-80% of their original strength. The most common types of damage in reinforced concrete structures are cracking in the tension zone, diagonal cracking in the core and loss of concrete cover, stirrups bursting outside, and buckling of main reinforcement, etc. [21].

In this paper, several completely different retrofitting techniques are considered. The seismic capacity of the existing RC buildings is based on lateral strength and stiffness. Bearing in mind that a restriction/change of the intended use of the building, or partial demolition thereof, is not possible, and so the improvement of its seismic capacity must be based on the lateral strength and stiffness. These requirements can be obtained with (i) the local retrofitting of existing elements, (ii) increasing lateral resistant systems with new structural elements (for example with concrete walls, concrete or steel moment frames or steel braced frames), or (iii) passive protection devices (dissipative bracing or base isolation) [22].

Examples of other retrofitting a structure may include reinforced concrete jacketing, steel bracing systems, fiber-reinforced polymer wrapping or jacketing, base isolation, damping devices, implementing a new structural element (RC walls), etc.

Concrete jacketing is based on the retrofitting of existing elements and entails increasing the sizes of columns and beams. This retrofitting technique is applied in order to increase the resistance and deformation capacities (flexural and shear) of the retrofitted elements. It is applied to columns and some beams, where the thickness of the jackets is defined according to the placements of both the longitudinal and transversal reinforcements. To reach the retrofitting goals, longitudinal reinforcements (steel bars) are continued between the stories, and the ties are placed in the beam–column joints [22]. Typically applied to buildings post-earthquakes or in aging structures, jacketing aims to prolong the structural integrity and lifespan of the building. In retrofitted structures, the introduction of column jacketing may lead to a change in the mode of failure and the redistribution of forces, potentially resulting in beam hinging. Therefore, thorough analysis and design considerations are essential to ensure the effectiveness and safety of the retrofitting process.

Steel bracing systems introduce additional lateral stiffness and resistance to seismic loads by incorporating diagonal braces into the building's framework. These braces are designed to absorb and dissipate seismic energy, reducing structural deformations and enhancing stability [23]. Steel bracing systems represent a robust retrofitting technique used to enhance the seismic performance of historical buildings, particularly those with timber-framed structures or other vulnerable lateral load-resisting systems. This method involves the strategic installation of steel braces or trusses within the building's framework to improve lateral stiffness, increase resistance against seismic forces, and reduce structural deformation during earthquakes [24]. Steel bracing systems offer several advantages for retrofitting historical buildings. They provide a cost-effective solution compared to more invasive structural interventions, allowing for targeted reinforcement of critical building components [25].

FRP wrapping involves applying composite materials around structural elements to enhance their strength and ductility. The high tensile strength of the fibers in the FRP materials provides reinforcement, while the polymer matrix ensures adhesion and durability [26]. The theory behind FRP wrapping is based on the composite action between the FRP and the existing RC structure, which improves the seismic performance by confining and reinforcing the structural elements. The primary objective of FRP wrapping is to improve the strength, ductility, and confinement of structural elements, thereby enhancing their ability to resist lateral forces and deformations during seismic events [27]. FRP materials, such as carbon or glass fibers, offer excellent tensile strength and durability, making them ideal for reinforcing vulnerable building components without adding significant weight or mass [28]. One of the key advantages of FRP wrapping is its versatility and adaptability to various structural configurations and geometries. FRP materials can be tailored to conform to complex shapes and contours, allowing for targeted reinforcement of critical areas within historical buildings while minimizing disruption to architectural aesthetics [29].

Base isolation is a sophisticated seismic retrofitting technique that entails the strategic installation of flexible bearings or isolators beneath a building's foundation to mitigate the effects of ground motion during earthquakes [28]. The primary objective of base isolation is to decouple the superstructure from the ground, thereby reducing the transfer of seismic forces to the building. This technique is particularly effective for seismically vulnerable historical buildings, where preserving architectural integrity is paramount while ensuring structural safety against seismic events [30]. One key characteristic of base isolation is its ability to significantly reduce the acceleration and displacement demands experienced by a building during an earthquake. By introducing flexible elements at the building's base, base isolation systems allow the structure to effectively "float" or move independently of the ground motion [31]. This dynamic response dissipates seismic energy and minimizes structural deformation, thereby enhancing the building's overall seismic performance.

Damping devices are advanced seismic retrofitting components designed to mitigate the effects of earthquake-induced vibrations and reduce structural response in historical buildings. These devices function by dissipating energy through various damping mechanisms, thereby controlling the dynamic behavior of structures during seismic events [32]. Damping devices are particularly valuable for historical buildings where traditional retrofitting methods may not be feasible due to architectural constraints or preservation considerations [33]. One of the primary advantages of damping devices is their ability to provide targeted and localized energy dissipation, allowing for precise control over structural response during seismic events. Unlike traditional retrofitting methods that may require extensive modifications to building components, damping devices can be installed discreetly within the building's structure, making them suitable for retrofitting projects where preservation of historical aesthetics is paramount [34].

The goal of implementing a new structural element is to increase the lateral strength of a new structural system. The position of the new RC walls is designed to optimize lateral stiffness and strength, as well as to reduce the stresses and displacements on the existing structural elements. The final layout is defined to minimize the impact on the existing RC buildings and optimize the construction of new foundations. The existing columns are incorporated into the new RC walls, and all the existing structural elements are connected to the new RC walls. This technique is applied only on the external frame without affecting the internal structural and non-structural elements [22].

5. CONCLUSION

Ensuring the resilience of structures against natural and man-made hazards is essential for mitigating losses and enhancing societal stability. Robustness, a key attribute of resilience, plays a crucial role in preventing catastrophic failures by ensuring that local damages do not lead to total structural collapse. The transition from Performance-Based Design to Resilience-Based Design highlights the growing emphasis on maintaining functionality and minimizing damage during disasters. Retrofitting techniques, including concrete jacketing, steel bracing, fiber-reinforced polymer wrapping, base isolation, and damping devices etc., offer effective solutions for enhancing seismic resilience. These methods not only improve the structural performance of existing buildings but also help preserve historical and critical infrastructure. By integrating resilience-focused strategies in both new construction and retrofitting projects, communities can reduce disaster risks, lower economic losses, and ensure the long-term sustainability of built environments. Investing in resilient structures is a proactive and cost-effective approach to disaster mitigation, ultimately safeguarding lives, property, and economic stability. The authors suggest a further investigation into the matter of the most effective and retrofitting intervention strategy. Case studies could also be conducted with emphasis on the behaviour of RC structures and buildings in un-retrofitted and retrofitted conditions. Moreover, combinations of different retrofitting techniques could be a subject of discussion. Future research should focus on enhancing the cost-effectiveness of retrofitting techniques to facilitate their broader implementation.

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