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Enhancing Buildings Resilience: A Comprehensive Perspective on Earthquake Resilient Design

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Introduction

People spend much of their time within buildings, and thus the safety and resilience of these buildings are essential for people's comfort and productivity. People spend about 90% of their time in buildings, whether in homes, offices, workshops, restaurants, stadiums, or hotels; thus, the safety of the buildings they occupy affects their productivity and quality of life [1, 2]. However, the safety of these buildings is not limited to the indoor environment but also extends to the structural safety and the functionality of supporting systems during and after disasters [3].

Extreme events and disasters have increased in pace and severity in recent years. These extreme events and their adverse effects have increased annually during the past two decades, fueled by the impacts of climate change [4–6]. These impacts are becoming more alarming, as countries across the globe are exposed to unprecedented events such as extreme precipitation and successive forest wildfires; these extreme events are projected to increase in the coming years [4, 7–9]. The impacts of extreme natural events are not limited to the emerging ones caused by climate change but also to reoccurring natural disasters such as earthquakes [10]. Earthquakes affect millions of people throughout the world and cause wide destruction to the urban centers and their inhabitants; they are projected to increase from more than 50% presently to two-thirds of the world population by 2050 [11–13].

Different disasters have different impacts on the built environment in urban areas, but earthquakes are among the most threatening. Extreme events affect different components of the built environment in urban areas, including buildings and other critical infrastructures, with the degree of each disaster varying on different parts. For example, a heatwave does not

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impact a building structurally, but it affects its thermal load and consequently, its electricity consumption and the electrical network throughout the city [3, 10, 14]. Some disasters may limit a building's functionality by impacting the supporting infrastructures directly, whether it is water, electricity, or transportation networks; the latter is significant during mega sport events, or indirectly due to failure propagation between the interdependent infrastructures [15–17]. However, earthquakes are different from other disasters in scale and destruction, impacting all infrastructures and buildings directly and indirectly through related disasters, such as tsunamis and landslides, or due to weak recovery [18–21].

To reduce the damage and cost of these severe events, the focus has turned to a resilience-based design in recent years. The increase in population density and value of urban areas has increased the cost of disasters [10, 16, 22]. The cost of a disaster can be divided into the cost of direct damage to the assets and population and the indirect cost due to downtime. Resilience in systems means reducing the direct and indirect damage to the system caused by disturbances and speeding up the recovery process [23]. Thus, integrating resilience-oriented thinking means designing structures and systems in a way that reduces the impacts caused by disturbances and limits the downtime to an acceptable level [24, 25]. Adopting resilience-based design thinking into structural engineering practices means expanding the structural design boundaries to the repair and recovery process, including the supporting systems, especially in extreme cases like earthquakes [25].

Earthquake resilience in structures should focus on both structural systems and functionality supporting systems. As the resilience concept focuses on preserving the overall performance during and after the earthquake, the design should accurately anticipate the structural performance of the building elements and the resulting drifts and deformations during earthquakes. Furthermore, supporting systems that are essential for the functionality and performance of occupants, such as heating, ventilation, and air conditioning (HVAC), electrical, and IT systems, should be accounted for to anticipate the possible damage and downtime. Due to the importance of reducing downtime and regaining functionality, which translates into cost, a resilience design should be based on a holistic understanding of the building's functionality and needs, with all pieces of equipment designed and fixed in a way that contributes to the desired resilience level. Such interdisciplinary understanding requires following an integrative design approach from the early stages of the project, with the participation of all stakeholders, to achieve resilience in a building.

To simplify the discussion regarding building resilience, we first discuss structural representation for assessing building resilience (from a structural perspective). Next, we discuss performance-based design (PBD) as the cornerstone of structural resilience assessment. Then, we focus on the role of supporting systems in building resilience. Finally, we end with concluding remarks, highlighting the importance of green building rating systems for improving the resilience of buildings.

Structural Resilience Representation

The concept of resilience has many representations in different fields aiming to facilitate measuring the resilience of the system of concern. Many representations are suggested in the literature, plotting the performance against time, most prominently in the work of

Bruneau et al. [26], who introduced the concept of the "resilience triangle" [10, 26, 27]. This concept allows one to quantify the resilience of the system by calculating the area under the performance curve, which is done through mathematical integration over time, from the moment of disaster to the end of recovery [34]. To further expand on the concept, readers can refer to [26].

The resilience of a building is not only related to the structural elements but also extends to the supporting systems; thus, there is a need to expand the resilience representation. Despite the critical importance of the safety and integrity of the structural elements, putting a building back in use also requires all the necessary supporting systems to function at an acceptable level [25]. Thus, we are suggesting a modified representation that reflects the actual requirements for building resilience, as presented in Figure 8.1.

The suggested representation for building resilience toward earthquakes, as shown in Figure 8.1, connects all the contributing systems to the building performance. These systems are divided into two main groups: structural systems and supporting systems. Furthermore, the supporting systems are divided into two categories: the first includes the systems necessary for the building's functionality that exist within the building perimeter, such as mechanical, electrical and plumbing (MEP), and the second consists of the supporting systems that exist outside the building and are critical for its functionality, such as electrical, transportation network, and all other critical infrastructures. The assessment of all these systems varies depending on their nature and scale, but they should be normalized to align with a structural system's main categorization levels, according to PBD: immediate occupancy (IO), life safety (LS), and collapse prevention (CP) performance. Additionally, the repair and recovery should follow a damage assessment process, and to ensure building resilience, the planned recovery efforts should be less than a certain time limit set during the integrative design step. The building performance is related to the lowest-performing system, reflects the building functionality loss, and can be used to quantify the resilience using mathematical integration, similar to the method mentioned in the previous paragraph.

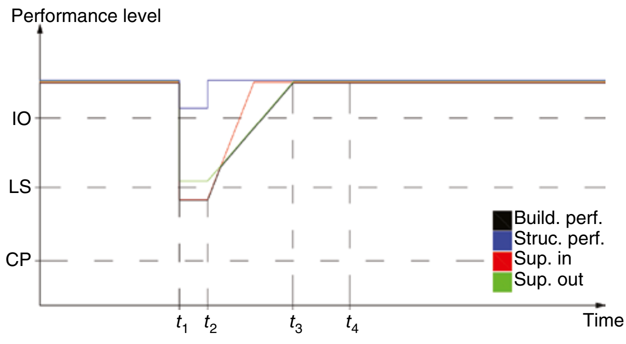

Figure 8.1 Building seismic/earthquake resilience representation. This representation connects various elements that contribute to the building's performance (Build. Perf.) and resilience toward earthquakes, namely structural system performance (Struc. Perf.), supporting systems within the building, such as MEP (Sup. In), and supporting systems outside the building, representing various infrastructures (Sup. Out). The used performance level notations are immediate occupancy (IO), life safety (LS), and collapse prevention (CP). The time-related ones are t_1: earthquake happens; t_2: the end of damage evaluation; t_3: the planned end of repairs; and t_4: repair time limit.

The discussion regarding the performance and assessments of the system is presented in the following section; however, the primary focus is on structural system performance assessment using PBD.

Performance-Based Design (PBD)

Structural resilience is related to structural design and construction, in other words, related to core and shell developments. This aspect should be addressed from a structural engineering perspective and focus on specific threats, primarily earthquakes. Structural resilience is not concerned with the structural safety under regular (bearing) loads, such as dead and live loads, because the capacity of bearing loads is considered ensured under current design codes. The main concern is structural behavior under exceptional events such as earthquakes/seismic loads, where design codes fail to describe the exact expected behavior of buildings. To address this limitation in design codes, the resilience-based approach relies on the application of PBD under several earthquake levels and probabilities to assess buildings' resilience and performance levels [28].

The response spectrum approach adopted for earthquake design fails to represent the actual damage to a building. The response spectrum relies on several properties related to project location and type of soil to generate a diagram of maximum responses that will affect a building based on the building's period [29]. The application of such a method mainly yields a shear force applied to a building that will generate internal forces in its elements and cause drifts. The aim of this design approach is to make sure all structural elements can sustain the resultant forces and keep drifts within allowable service levels. The main drawback of this method is to view a building as a simple oscillator and convert an earthquake, which consists of a series of unpredictable vibrations with numerous frequencies, into a single force that affects a building linearly. This simplification ignores the actual impact of an earthquake and the development of plastic hinges in a building, which can change a building's response and periods under a possible series of vibrations contained in an earthquake.

PBD provides better insights into a building's behavior under earthquake conditions than conventional response spectrum analysis. By leveraging the increased computational power in recent years, structural engineers are capable of simulating building behavior under specific ground shaking records, representing earthquake scenarios, in what is known as time-history analysis. Unlike the response spectrum analysis, which is limited to the application of static forces at story levels, time-history analysis reflects the actual building behavior and allows for monitoring of energy dissipation solutions and the development of plastic hinges throughout an earthquake scenario. Energy dissipation and development of plastic hinges are then used to describe a building's performance level.

PBD can account for the randomness of earthquakes by using several earthquake records. To address the random nature of earthquakes and the vast range of possible frequencies, PBD requires running a series of specifically selected ground shaking records based on the geological properties of the building area. These properties are related to site classification, such as fault type and distance, and project soil, which affects wave velocity.

Synthetic accelerograms can be generated and used when suitable records are lacking. However, a large database of ground motion records from around the world can be accessed through [30]. Although, the records accessed through this database are unscaled, a tool is provided on the website to generate scaling factors that can be applied in the simulation software [30].

Generally, ground motion records require scaling to match earthquake spectrums at different levels and probabilities of reoccurrence. The scaling process is typically done in the time domain and follows two main approaches: scaling over a single period of interest and scaling over a range of interests. The first approach focuses on making the response spectrum of the record at the natural period of the structure (T_n) equal to the code-provided response spectrum at the same point. The second approach focuses on using a scaling factor that considers the average variations between periods over a range from $0.2T_n$ to $1.5T_n$. Alternatively, engineers can apply spectral matching, which manipulates the frequencies, to smooth the differences between the records and the target in the time domain. However, spectral matching is not recommended as it changes the frequency content of the ground motion records.

Several performance objectives, or levels, are assigned to different earthquake probability levels. PBD aims to assess the structural behavior under scaled ground motion records and ensure it does not exceed the performance limit defined by the formation of hinges and development associated with each earthquake level. The main performance objectives are IO, LS, and CP, referring to the development of several levels of plastic hinges in the building; readers can expand on the topic by referring to [25, 28, 31]. These performance criteria are then assigned to specific levels of earthquake probability of exceedance such as 2% in 50 years equal to an exceedance level of once every 2500 years event and 10% in 50 years equal to once every 475 years [25, 28].

Planning for the post-earthquake assessment and repairs is essential to ensure the resilience of the building and its timely recovery process. From the early design process, scenarios of a post-earthquake event should be considered, such as a lack of resources for damage assessment and retrofitting. To accommodate such a situation and to avoid unnecessary downtime or risk the lives of occupants, building owners should have binding contracts with professional experts to assess the damage suffered to the structural elements and with contractors to apply any necessary retrofitting before reoccupying a building. The time needed for such an assessment as well as the mobilization of the contractor should be determined through the contracts and accounted for as part of a building's recovery time. Additionally, the details of these contracts, both in time and cost, should be based on the results of a peer review process of the PBD results.

Supporting Systems

Several aspects can affect building resilience, especially regarding the supporting systems, which are necessary for the building's functionality and achieving performance goals. These systems can be divided into two main categories: within the building, such as MEP, and offsite/external supporting systems, such as critical infrastructures.

Supporting Systems Within the Building

Resilience-based thinking should extend beyond the structural element's performance during an earthquake, as the survivability of nonstructural components is also important in labeling a building as resilient. In a resilient building, it is mandatory to ensure that all nonstructural components suffer acceptable degradation levels that do not prevent the system from meeting its intended performance goal. For example, if the damage due to shaking affects a building's envelope, causing severe cracks and threatening the safety or comfort of occupants, the building may not be suitable for immediate occupancy, even if the structural parts meet the required performance levels; the same concept can be applied to the MEP.

The assessment of these nonstructural systems should include facades, electrical, Internet, HVAC, and plumbing systems. To prevent any impact or loss beyond the scope allowed by the intended performance, the assessment of such systems should include checks on the impacts of oscillation, drifts, and ductile deformation, as well as confirming proper installation and repair of related equipment. Such assessments are mandatory to evaluate possible damage and the recovery of resources and time, thus creating a holistic understanding of building earthquake resilience. Such consideration can allow the application of the suggested representation of Figure 8.1, which facilitates the capture of the recovery plans and the assessment of different system alternatives based on the expected recovery rates, costs, and supply complexities. Furthermore, it is crucial to ensure the availability of maintenance and repair teams and equipment, through pre-disaster contracts, to avoid prolonged downtime due to either a shortage of equipment or resources during the post-disaster period. These considerations are essential when designing a resilient building because a damaged HVAC system, lightning, or any other system may limit or eradicate a building's functionality.

Beyond the Building Limits

Urban infrastructures are essential to a building's functionality and, thus, to its resilience. Critical infrastructures such as transportation, electricity, water supply, and sewer networks are essential to the livelihood of any city. In the aftermath of an earthquake, these infrastructures are crucial for the relief effort. For example, transportation networks facilitate the mobility of repair teams and equipment and allow the return of a building's occupants.

The performance assessment of infrastructures under conditions of earthquakes is different, in scale and nature, from the one done for the structural system; thus, it should be done separately and provided by the governing authorities, such as municipalities. A governing authority should assess and map the performance and damage expected to be suffered by critical infrastructures due to earthquakes. Such an assessment should consider the possible damage caused to each infrastructure at each magnitude of earthquake reoccurrence probability, similar to those applied in PBD, as part of the regulating codes and building standards. Additionally, it is necessary to reflect the degradation and delays caused by the interdependency between different infrastructures, such as inaccessibility to a substation due to loss of a bridge or loss of metro services due to the damage of the electrical network. The results of these assessments should be mapped to reflect the expected damage, serviceability level, expected downtime, and recovery duration; such a process should be done in a Geographic Information System (GIS) environment and provided either publicly or on-demand to the developers.

The use of microgrid applications and on-site energy production can help improve resilience. The application of microgrids and energy production using renewable energy could provide some level of functionality for the related system, especially if the design that is considered works on an islanded mode with enough energy storage capacity [3]. However, due to the debris of an earthquake, these systems are also susceptible to direct and indirect impacts, and their efficiency is related to climate factors and storage capacity. On-site energy production using a backup generator could provide a temporary solution, but its safety and the risk of a lack of fuel supply in the post-earthquake period could limit its reliability.

Conclusion

With the increased concentration of people living in urban areas, it is becoming more critical to reduce the impact caused by any disturbance, especially large-scale ones such as earthquakes. With the large number of cities located in active seismic areas and the increase in population concentrated in them, the impact of any future earthquake is expected to be more disastrous. The impact of an earthquake can span over large areas and affect buildings, infrastructures, and even the sociology of humans. It is crucial to base preparation and risk management planning on two main principles: impact reduction and swift recovery, i.e., resilience-based planning. Resilience-based planning should expand to the design standards and practices of buildings and infrastructures and consider their interactions, especially with high-value facilities. Furthermore, designers should consider all the supporting systems within the building and the earthquake's impact on these systems. Considering all the systems within and outside the building, in addition to its structural system, can provide a holistic understanding of the impact of such an event and facilitate efficient recovery planning, thus protecting human and economic capitals and improving building and city resilience.

Aiming for efficient design and performance of a building by following green building regulations can also improve its resilience to any disturbance, including earthquakes. By following green building rating system recommendations and requirements, such as LEED or BREEAM, engineers can develop an efficient design, in terms of ventilation, natural lighting, and energy and water consumption [32]. Additionally, these rating systems promote on-site energy production and water reuse, extending the survivability of the building and its occupants [32, 33]. Furthermore, following resilience-oriented rating systems, even if not fully adopted, can substantially improve the resilience of a structure. Most notable among these rating systems are REDI, developed by ARUP [25], which focuses on earthquake resilience, and RELI, developed by USGBC [33], which focuses on the resilience of a building to different disturbances.

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