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Review Article

Comprehensive Review of Community Seismic Resilience: Concept, Frameworks, and Case Studies

H'ng Chee Yin, Moustafa Moufid Kassem, and Fadzli Mohamed Nazri

School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

Correspondence should be addressed to Fadzli Mohamed Nazri; cefmn@usm.my

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Seismic resilience is a concept to evaluate the postearthquake functionality of structures that significantly play a critical role in postearthquake rescue and recovery. Indeed, the community is made up of more than just buildings; it is also made up of other subsystems such as hospital and school facilities as well as roads, drainage systems, sewer systems, and electrical power transmission networks. In recent years, the concept of community resilience as a tool for disaster risk management has attracted substantial attention from all parties, such as governments, designers, decision-makers, and stakeholders. Community resilience can be assessed more effectively by using a multi-disciplinary approach that takes into account the community's uncertainties, as opposed to a single-criteria approach. The global community resilience model must be long-term validated and dependent on the most vulnerable and low-resilience portions of the community, according to a prior study. According to the review of the seismic resiliency studies performed in the recent decades, the frameworks for the quantification assessment of the community resilience are explained. Moreover, several case studies for community resilience and the application of different subsystems are reviewed and elaborated in this paper. Based on these resilience studies, the main challenges on the effectiveness of the resilience assessment are the availability and accessibility of the data, the financial resources, and the cooperation from all the parties.

1. Introduction

In the past centuries, many earthquakes that happened around the world were recorded in history. Recent major earthquakes such as the Sumatra Earthquake with a magnitude of 8.6 (also called as Indian Ocean earthquakes) which occurred in 2012 had reported 10 deaths and 12 injuries; Tōhoku Earthquake with a magnitude of 9.1 which occurred in 2011 had destroyed over one hundred thousand buildings in Japan, caused nuclear accidents and over ten thousand deaths were reported; Maule Earthquake with a magnitude of 8.8 (also known as Chile earthquake) which occurred in 2010 had damaged the port at Talcahuano and collapsed several buildings in many cities; and Valdivia Earthquake with a magnitude of 9.5 which occurred in 1960 was the most powerful earthquake ever recorded in the history. From the Earth's history, an earthquake will cause a lot of impacts to the communities such as the collapse of structures, casualties, economic loss, and other tragedies.

In the aspects of sustainable development of the society and communities, structural systems such as buildings, water supply plants, and power supply plants play key roles to achieve sustainability. Due to the difficulties and challenges of recovery and reconstruction of structural systems of the communities in postseismic events, the seismic performance, and the structural properties of the systems such as resiliency, redundancy, and robustness have raised the significant interests of the stakeholders, government, and designers.

Seismic resilience is a concept to evaluate the post-earthquake functionality of structures that significantly play a critical role in postearthquake rescue and recovery [1]. In the event of an earthquake, seismic resilience is the ability of a building to continue operating normally after the initial damage has been repaired [2]. Aside from that, seismic resilience is considered as an alternate method of dealing with the issue of functionality, which has been disregarded in earlier or existing seismic code developments [3]. Previous

seismic design codes such as British Standard have not taken the consideration of the seismic effects in the structure design process, thus, this may lead to the increase in the risk of the structures designed using the design codes without consideration of seismic effects when subjected to the earthquake events.

Multiple frameworks have been proposed and used in recent years to assess the seismic resilience of structures that have been built over the past century [4–7]. Some of the frameworks proposed by Cimellaro et al. [8] include a quantitative definition of resilience based on an analytical function that can be used to both technical and organizational concerns. Cimellaro et al. [9] has been created a complete model for quantifying the catastrophe resilience of a hospital system that incorporates both loss estimating and recovery models that can be used to critical facilities. Verrucci et al. [10] proposed an evaluation of multi-disciplinary indicators for the seismic resilience of metropolitan areas that would be comparative and disaggregated. Besides, the transportation system, and the electric power supply system functionality is considered one of the most important critical infrastructures to have a seismic resilience in the community. Zhao and Sun [11] examined the impact of looped interdependences among Critical Infrastructure Systems (CISs) on their seismic resilience, by proposing an agent-based modeling (ABM) framework. In such a framework, the coupled Transportation System (TS) and Electric Power Supply System (EPSS) have been included. The developed framework is able to delineate the postshock recovery of the coupled TS-EPSS-Community. Similarly, for the functionality of road networks, water systems, electric power, and the resilience of the affected bridge damages and restoration, surrounded by urban areas [12–15].

Moreover, a framework for assessing the seismic resilience of urban hospitals based on fault tree analysis has been developed and tested (FTA) by Yu et al. [3]. Shang et al. [16] proposed a quantitative framework to assess the seismic resilience of the hospital systems which consists of four stages: the seismic hazard analysis, the fragility analysis, the seismic risk analysis, and lastly the calculation of the seismic resilience. Nevertheless, simple resilience evaluation metrics for the quantification and appraisal of resilience have been proposed by Yarveisy et al. [17] which are based on the concepts of dependability and maintainability, as well as the system modeling methodology, and are easy to implement. Moreover, measuring community resilience is an essential work for municipal policy makers towards a unified approach [18]. He et al. [19]conducted a comprehensive assessment on community resilience adapted to the fire following earthquakes (FFE) scenarios. Yet, in terms of computational approaches, these frameworks still need to adequately address community interdependencies and consider the impact of decision-making in modeling. Melendez et al. [20], Koliou et al. [21], and Marasco et al. [22] provided studies and reviews in terms of computational methods to model community resilience, progress and challenges to have a resilience community, and an integration platform to assess seismic resilience in communities by focusing on the last few decades.

In this study, several methods and framework for assessing and quantifying the seismic resilience index of structures are described in this review paper. The assessment of building structures is examined by utilizing the functional curves, and obtaining the direct and indirect loss functions, as well as the time recovery functions. However, a community not only consists of buildings but also consists of other subsystems such as bridges, road and drainage systems, sewerage systems, power transmission systems, and other fundamental subsystems. Therefore, the applications of the seismic resilience index approach in a community system which had been performed by previous studies are also introduced.

2. Concept of Seismic Resilience Index in Post Seismic Event

2.1. Community Resilience in Disaster Situation. The perception of community resilience has gained extraordinary attention in recent decades since the community is very first responder toward any disaster. The researcher that first introduced the term "resilience" in ecology has defined it as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between the population or state variable" [23]. However, the term "resilience" is now more specifically defined as "the contribution in the establishment of the capacity or ability to rebuild back effectively after a tragedy" [24]. Natural catastrophes such as earthquakes, floods, fires, landslides, and Hurricane winds have resulted in both social and physical consequences, with civilian deaths and damage to buildings and infrastructures being among the most severe.

There are four levels of achievement proposed for the community resilience which is illustrated in Figure 1, namely (1) Better bounce back refers to a community that can absorb disturbances and function better than before the crisis; (2) The ability to bounce back refers to a community's ability to return to predisaster state, (3) It is tough to recover but worse than before, referring to the community's reduced ability to recover, and (4) collapse which refers to the community that incapable to function after faced the disaster [25–27].

2.2. Community Resilience Framework. In the early decades, the resilience of the communities is proposed and evaluated qualitatively and conceptually which has less real and effective. The community resilience index can be acted as a baseline in monitoring the changes of the community over time through a set of indicators in several aspects such as socio-demographic, economic, environmental, organizational, infrastructures, and cultural [28]. Furthermore, the concept of the resiliency of the communities is seldom used as a tool in seismic risk management and mitigation due to the limited political and specific planning activities [29]. Consequently, a reconstruction process is deficient and economically ineffective due to the lack of accurate and appropriate mitigation strategies.

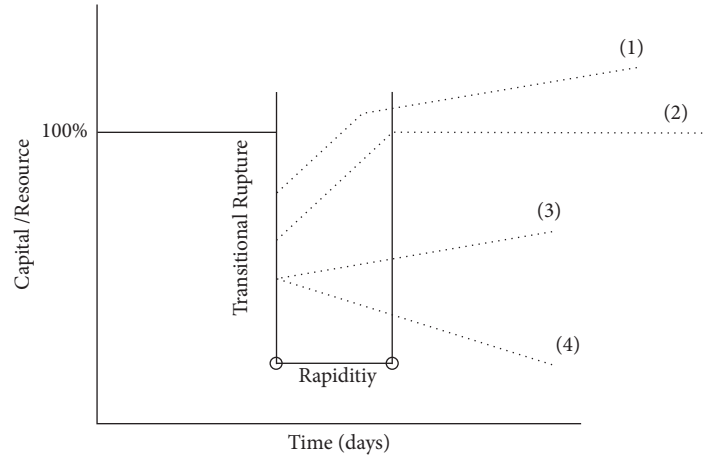

Figure 1: Resilience concept in the schematic.

Recently, several classic frameworks which effective and useful for single systems of the whole community have been introduced to assess the resilience of communities. For example, a framework that links community resilience to the seismic performance of buildings had been proposed by You et al. [30]. The framework is schematized as Figure 2.

The probabilistic seismic performance assessment (PSPA) in this framework is targeted to investigate the correlated seismic performance of buildings. The seismic performance is depicted in terms of the collapse capacity curve, the recovery time function, and also the cumulative distribution function of the repair cost. These seismic performance characteristics are used as inputs to the framework's network-based recovery model. Refers to Figure 2, by adapting the seismic performance parameters, the estimated community loss due to the seismic excitation can be evaluated through the network-based recovery simulation. Thus, the resilience index of the community can be calculated by performing the postseismic simulations. However, the existing frameworks require modification and improvements to predict the whole community while accounting for the influence of the interaction between the subsystems of the communities.

Didier et al. [31] developed an innovative compositional demand catastrophe resilience assessment framework for critical facilities in civil infrastructure systems, which was designated Re-CoDeS (Resilience–Compositional Demand/Supply). The framework is comprised of three major components, namely, the demand layers, the supply layers, and the manage system service model. In the framework, the resiliency of the civil infrastructure system was evaluated through two major dimensions: the resilience at a component level which represents the amount of supply of the particular components, and the resilience at a system level which occurs when the service demand exceeds the available supply at any component of a system. Moreover, the resilience time of the components and the systems were assessed. The authors highlighted that the framework was able to be used for variety of recovery priorities as well as the evaluation of recovery rates in a variety of community system configurations. However, the examination of the consequences of interconnection and dependency of the investigated civil infrastructure system with other systems is one of the most difficult challenging tasks for the frameworks.

Maroufi and Borhani [28] proposed a framework to evaluate the community seismic resilience in subcity districts of Mashhad, Iran. The framework consists of six resilience dimensions and each of the dimensions employed a set of measurables indicators. The resilience dimensions defined in the framework include the economic dimension, the socio-demographic dimension, the environmental features, the organizational dimension, the physical or infrastructure dimensions, and the cultural or community competence dimension. A total of 23 indicators were selected for the framework as summarized in Table 1. The authors highlighted that a more comprehensive assessment of the seismic resilience for a community could be achieved by taking into consideration of these fundamental dimensions of a community into the framework. However, one of the limitations of this framework was the availability of the data required for the indicators.

Furthermore, Svetina et al. [32] had performed an analysis of pandemic risk management within a resilience framework on the two 2020 Zagred earthquakes and the COVID-19 pandemic. The occurrence of the pandemic was considered into the concept of seismic resilience of the community in the framework. In the study, the testing intensity after the earthquake was observed to present the seismic resiliency of the community within an ongoing pandemic. As the earthquake destroyed the hospital systems, the natural responses of hospitals to the seismic excitations subsequently influenced the disease transmission rate due to the increased socializing of citizens after the seismic events. The results of the study indirectly highlight the importance of the improvement of the resiliency of a community, especially during a pandemic.

Using a hybrid information fusion framework, Chen and Zhang [33] proposed a method for evaluating the earthquake resilience of regional areas at an early stage. The framework was proposed based on the basic probability assignments (BPAs) and the Dempster-Shafer (D-S) evidence theory

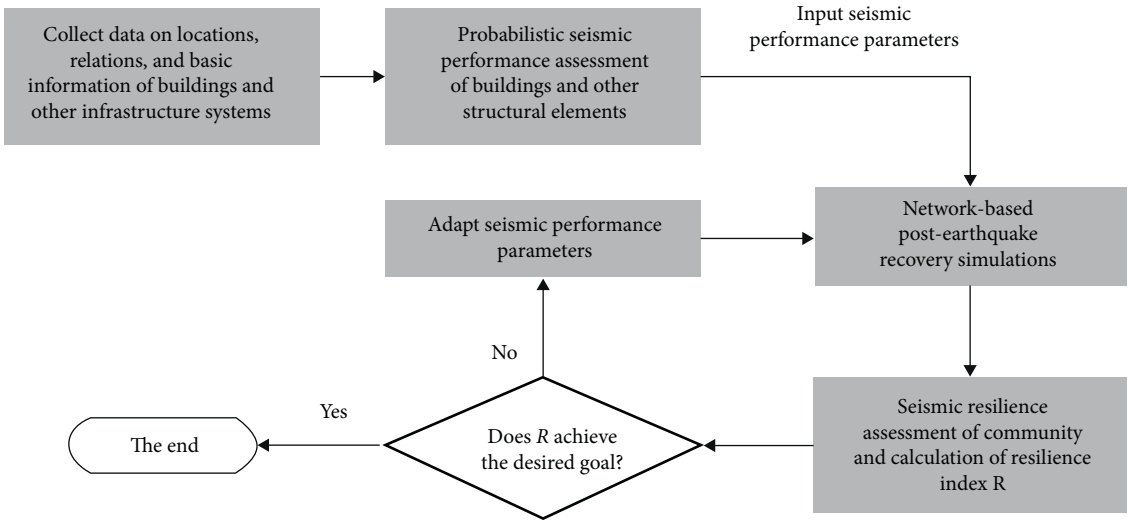

Figure 2: The flowchart of the framework [30].

Table 1: Summary of community seismic resilience indicators for each dimension and the main attributes of the dimensions. [28].

Category/dimension	Indicators
Economic (occupation, housing capital, financial capital, economic diversity)	(1) Percentage of employed population (2) Percentage of home ownership (3) Number of construction licenses issued by the district municipality in the last fiscal year (4) Ratio of large to small business
Socio-demographic (population exposure to hazard, education level, age, special needs)	(1) Number of populations per 1,000 square meters (2) Percentage of the population within high-risk zones (3) Percentage of people with higher education level (4) Percentage of populations aged between 6 and 65 (5) Percentage of people with physical or mental disability
Environmental (exposure, vegetation, vulnerability of place, land slope)	(1) Percentage of the areas with a slope of more than 4% in the neighborhood (2) Natural or green areas per capita
Organization/Managerial (managerial resources, managerial process, managerial qualifications)	(1) Municipal budget line of each district for crisis management and prevention (2) Number of emergency management maneuvers (3) Number of neighborhood emergency response volunteers per 1,000 people
Physical/Infrastructures (physical capital, infrastructural capital, physical exposure to hazard)	(1) Percentage of the deteriorated urban fabric (2) Number of healthcare centres per 1,000 residents (3) Number of emergency shelters per 1,000 people (4) Percentage of critical infrastructures located inside high-risk areas
Cultural/Community competence (social trust, religious ties, cultural features, community participation, public satisfaction)	(1) Inhabitants' perception of social trust (2) Number of mosques and other religious-based per 1,000 residents (3) Number of phone calls to public relation centre of each subcity district per 1,000 residents (4) Inhabitants' satisfaction toward life (5) Percentage of satisfaction from local councils

which is capable of integrating evidence from various sources with epistemic uncertainty. The proposed framework was employed in the regional areas of Nepal with the consideration of three dimensions, namely geological dimension, building dimension, and social dimension. Table 2 summarize the indicators of each dimension adopted in the framework. The authors highlighted that the proposed framework can be applied to other earthquake-prone areas and suggested involving infrastructures in the framework to achieve a holistic digital twin framework. Other than the

Table 2: Summarizing the indicators for each dimension [33].

Dimensions	Indicators
Geological	(1) Acceleration with a likelihood of reaching 10 percent in 50 years is predicted to occur (2) Distance to nearby active faults (3) Shear-wave velocity down to a depth of 30 m
Building	(1) Type of foundation for a building (2) Type of internal wall of a building (3) Building roof type
Social	(1) Density of the inhabitants (2) The proportion of the population aged between 15 and 64 (3) The proportion of people over the age of 25 who have high school or a higher degree

aforementioned frameworks, Table 3 summarizes the frameworks proposed and introduced in previous studies. Those frameworks applied the quantitative data to measure the seismic resiliency of the communities at different geographical scales.

2.3. Seismic Resilience Improvement in Communities. Due to the ineffective and weakness of the conceptual framework in assessing the resilience of a community, a new seismic communities resilience model is introduced to improve and quantify the resilience of the communities probabilistically. This new model which was proposed by Vona et al. [29] is aimed to define the mitigation strategies based on the prioritization of the retrofit interventions to increase the resiliency of the communities and to address the economic resources on the low seismically resilient areas and building types. In the way of explanation, the resiliency of a community is considered all the essential independent systems of the community, for instance, residential, transportation, urban systems, utility systems, and other systems. The main roles of these systems in emergency management and the prioritization of the functionality strategies shall be identified to recover the functionality of the community in the essential dimensions such as socio-economic, managerial, and technical. However, the functionality of the residential buildings is still depleted when other systems are ready to provide services.

Therefore, in the new model, the relationship between community resilience and the residential building's performance is emphasized and defined. Subsequently, the new probabilistic methodology was proposed by the authors for the housing system based on the seismic reconstruction process data which will provide a more accurate numerical analysis. The new methodology considered the vulnerability of the building types, the economic resources, and the damage levels which influenced the recovery time in the analysis. Figure 3 illustrated the new proposed qualitative trend of a community's functionality function in postseismic events.

The conceptual model emphasizes the reliance of the overall resilience on the residential system as a source of information. Following the explanation provided by Vona et al. [29], with reference to Figure 3, the grey regions represent the fundamental subsystems of the community such as hospitals and highways as well as water, sewerage and electric power supply, whose functionality should be prioritized. The blue area, on the other hand, corresponds to the residential system. The authors distinguish three major components of the new model: a rapid return to functionality in the short term; a pseudohorizontal step that is linked to the planning and mitigation of preliminary activities for the reconstruction process; and an increasing branch that is based on the distribution of financial funding and the corresponding repair activities. In this sense, the resiliency of a community may be expressed as the ability of a community to maintain a specific level of performance while also restoring the state that existed prior to the seismic event.

Consequently, Vona et al. [29] mentioned that the total control time and the final functionality level of the whole community including the housing systems are not only influenced by the seismic effect and also by the decision phase and implementation phase of the reconstruction process and the availability of the financial resources from the parties and based on the damage levels which refer as the L'Aquila reconstruction process.

3. Seismic Resilience Index Approach

3.1. Functionality Curve. The fundamental purpose of resilience is to evaluate the functionality of structures after an earthquake event. Based on the damage level and the functionality of a structure postseismic event, the recovery period for a structure to rehabilitate its structure purpose or function which safe for end-users can also be evaluated. The functionality of a structure is commonly defined and expressed in the terms of direct and indirect economic losses due to earthquakes, direct and indirect causalities losses, structure recovery time, and business or function interruption time. Moreover, the level of functionality of the structures is defined depending on the types of structures. For instance, the level of functionality of a hospital or a health care centre is basically defined based on whether the hospital or health care centre is able and safe to provide the emergency medical services whereas the level of functionality of residential buildings can be defined based on whether the buildings are safe for residents to occupied for a particular serving period.

The functionality curves are developed and utilized for evaluating the seismic resilience of the structures. Generally, the functionality curves can be evaluated with the use of

Table 3: Summarization of community seismic resilience frameworks.

Author	Framework	Main dimensions	Methodology of framework development
Sauti et al. [34]	Vulnerability index	Exposure module, resilience module, capacity module	Literature review, theoretical assumptions
Peacock et al. [35]	Community disaster resilience index (CDRI)	Social, economic, physical, human capital	Literature review
Bastaminia et al. [36]	Disaster resilience	Social, institutional, environmental and physical, economic	Literature review
Rus et al. [37]	Disaster resilience	Building, infrastructure, community, open space	Literature review
Alshehri et al. [38]	Framework of community resilience to disaster	Social, economic, physical, and environmental issues, governance, health and well-being, and information and communication technologies are all covered in this research.	Three-round delphi study
Alshehri et al. [39]	Community resilience disaster framework (CRDSA)	Social, physical and environmental, economic, health and wellbeing, governance, information and communication	Delphi expert survey and analytic hierarchy process (AHP)
Asadzadeh et al. [40]	Disaster resilience index	Urban land usage and dependent population, socio-cultural capability, life quality, open space, social capital, emergency infrastructure, economic structure	Literature review, factor analysis (FA), analytic network process (ANP)
Cutter et al. [41]	Community resilience	Social, housing or infrastructural, community capital, economic, institutional, environmental	Literature review
Ainuddin et al. [42]	Community resilience index (CRI)	Physical, social, economic, institutional	Literature review
Burton [43]	Disaster resilience	Social, economic, institutional, infrastructure, community, and environmental systems resilience.	Literature review, factor analysis (FA), reliability/item analysis (Cronbach's alpha), multidimensional scaling (MDS), multivariate analysis procedure
Verrucci et al. [10]	Multi-disciplinary framework for seismic resilience	Planning with land-use, built-in resilience, continued functioning or redundancy of critical service and infrastructure, distribution of resources, social cohesion	Literature review, system diagram
Sherrieb et al. [44]	Community resilience index	Economic development, social capital	Literature review
Cutter et al. [45]	Disaster resilience of place (DROP) model	Ecological, social, economic, institutional, infrastructure, community competence	Literature review

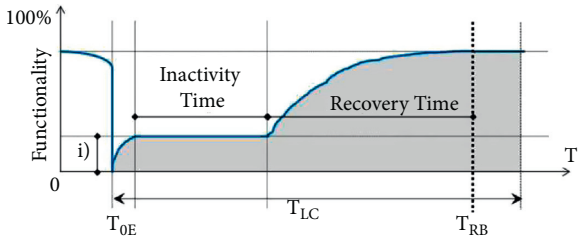

Figure 3: Conceptual seismic resilience measurement of whole communities [29].

fragility curves or vulnerability curves. The functionality curve which also known as the resilience curve defines the functionality of a structure in percentage over the control time. The functionality curve is developed by using the functionality function which is a nondimensional quality system function. The functionality of a structure can be evaluated using several indicators such as direct loss, indirect loss, and recovery time. Figure 4 shows the schematic of the functionality curve which is commonly used by previous studies [3, 8, 16, 46, 47].

The functionality function was first introduced by Cimellaro et al. [8]. The functionality function is also a nonstationary stochastic process and it is usually indicated as $Q(t)$. According to Cimellaro et al. [8] and by referring to the schematic of the functionality curves shown in Figure 4, the seismic resilience functionality function is expressed as in (1). The values of the quantities in the function are less than 1 since the desired full functionality is 100% functionality which is indicated as 1.0 in the function.

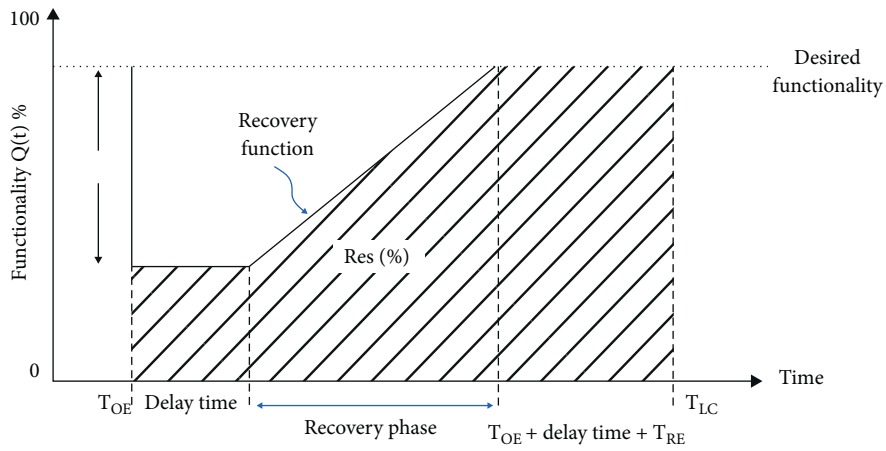

Figure 4: Schematic of functionality curve that commonly adopted [8].

$$Q(t) = [1 - L(I, T_{RE})].\{H(t - t_{OE}) - H(t - [T_{OE} + T_{RE}])\}.f_{\text{REC}}(t, T_{OE}, T_{RE}), \quad (1)$$

where, $L(I, T_{RE})$ is the loss function, $f_{\text{REC}}(t, T_{OE}, T_{RE})$ is the recovery function, T_{RE} is the recovery time after an event, T_{OE} is the time occurred event with intensity, and $H(t)$ is the Heaviside step function.

3.2. Loss Function: Direct and Indirect Losses. In general, the loss function is the combination of direct loss and indirect loss and is expressed as (2) [8]:

$$L(I, T_{RE}) = L_D + (\alpha_1.L_I), \quad (2)$$

where L_D and L_I represent the direct losses and indirect losses, respectively, whereas is the weight factor that depends on the significance of the structures for the society and the influence of the structure on the other system.

Direct losses due to earthquakes refer directly into quantifiable losses which occur instantly during a disaster, for instance, the number of fatalities or injuries and replacement or repair cost of damaged structures. Moreover, for a building, the direct economic losses also refer to the physical structure, and nonstructural impact caused by the disaster or seismic event. Thus, the direct economic losses are defined as the ratio of building repairing costs to the replacement costs. As mentioned previously, the functionality curves can be developed using fragility curves or vulnerability curves. By using the fragility curves to develop the functionality curves, the direct loss of the structural or nonstructural member k is calculated using (3) [8]:

$$L_{DE,K} = \sum_{j=1}^{n} \left[\frac{C_{S,J}}{I_S} \prod_{i=1}^{t_i} \frac{1+\delta_i}{1+r_i}\right].P_j\left\{U_{i=1}^{n}\left(R_i \geq r_{\lim,i}\right)|I\right\}, \quad (3)$$

where, P_j is the conditional probability of exceeding a performance limit state j, when an extreme event of intensity I occurs, $C_{s,j}$ is the building repairing costs related to a j damage state, I_s is the replacement building costs related to a j damage state, r_i is the annual discount rate applied for the time interval in years between initial investment and the extreme event, and δ_i is the annual depreciation rates.

Thus, the direct economic losses for a structure are computed using the weight average expression as shown in (4) [48]:

$$L_{DE}(I) = \frac{\sum_{k=1}^{n} W_k.L_{DE,K}}{N}. \quad (4)$$

where is the weight factor representing the importance of each structural and nonstructural element in a structure or building and is the total number of structural and nonstructural elements in a structure or building. Furthermore, the term $\sum_{j=1}^{n} P_j\left\{|U_{i=1}^{n}(R_i \geq r_{\lim,i})|I\right\}$ in (4) is derived from the fragility analysis.

Direct causalities losses are defined as the ratio of the number of people injured inside the building to the total number of occupants inside the building. The direct causalities losses are calculated using (5) [48]:

$$L_{DC}(I) = \frac{N_{in}}{N_{tot}}, \quad (5)$$

where N_{in} is the number of people injured in the fatal and nonfatal manner depends on several factors such as the time of the day of the seismic event, the age of the population, and the number of available hospitals. Meanwhile, N_{tot} is the total number of occupants in the building.

Other than fragility curves, the vulnerability curves can also be used to assess the loss function by using the modified expression as shown in (6) [8]:

$$L_{DE,K} = \left[\frac{C_S}{I_S}.\prod_{i=1}^{t_i} \frac{1+\delta_i}{1+r_i}\right].\text{Damage}(\%), \quad (6)$$

where C_S is the building repair costs, I_S is the replacement building costs, δ_i is the annual depreciations rate, r_i is the is the annual discount rate applied for the time interval in years between initial investment and the extreme event, the

Damage (%) is the percentage obtained from the vulnerability curve.

Both the fragility curves and vulnerability curves can be used to assess the loss function. However, the loss function can be calculated quickly by using vulnerability curves which are sufficient to calculate the percentage of estimated damage of a structure. Moreover, throughout the study performed by Samadian et al. [46] the authors concluded that the results of resiliency extracted from the vulnerability curves are more ideal than those extracted from the fragility curves. Whereases Kassem et al. [49] provided the basic steps that's involved in developing the seismic resilience index for a particular building from vulnerability and fragility curves as shown in Figure 5.

Indeed, the depreciation of a building is the process of methodically deducting the documented cost of the building from its current value until it hits zero or is no longer worth salvaging the building [51]. The annual rate of depreciation varies depending on the type of building being depreciated. The annual rate of depreciation for various types of buildings is summarized in Table 4. Furthermore, the yearly rate of depreciation can be calculated as the reciprocal of the asset's useful life.

In the construction industry, the discount rate is defined as the percentage rate required to calculate the present value of a future cash flow, moreover, it is also a factor reflecting the time value of money that is used to convert the cash flows occurring at different times to a common time base [52]. In the other words, a discount rate is used for bringing future costs to a comparable time base. The annual discount rate can be calculated using (7) where is the number of years [51].

$$\text{Annual discount rate}, r = \left(\frac{\text{future cash flow}}{\text{present value of asset}}\right). \tag{7}$$

Indirect losses due to the seismic excitation refer to the subsequent results of the initial destruction such as the business interruption losses and revenue. Similar to direct losses, the indirect losses also involved two contributions: indirect economic losses and indirect causalities losses. The indirect economic losses are time-dependent and difficult to quantify due to different expression forms. They can be expressed in the terms of business interruptions, rental income losses, or revenue expenses. Furthermore, indirect causalities losses are defined as the ratio of the number of injured people outside the building to the total population of the area. Thus, the indirect causalities losses can be calculated using (8) [48]:

$$L_{IC}(I) = \frac{N_{\text{in}}}{N_{\text{tot}}}, \tag{8}$$

where N_{in} is the number of people injured outside the building and N_{tot} is the total population of the affected area.

Finally, as suggested by Cimellaro et al. the total direct losses computed by direct economic losses and direct causalities losses can be calculated by using :

$$L_D = (L_{DE})^{\alpha_{DE}} . (1 + \alpha_{DC} L_{DC}), \tag{9}$$

where α_{DE} is the weighting factor related to the construction losses in economic terms while α_{DC} is the weighting factor related to the nature of occupancy. Next, the total indirect losses which are computed by indirect economic losses and indirect causalities losses can be calculated by using :

$$L_I = (L_{IE})^{\alpha_{IE}} . (1 + \alpha_{IC} L_{IC}), \tag{10}$$

where α_{IE} is the weighting factor related to the construction losses in business interruption while α_{IC} is the weighting factor related to the nature of occupancy.

3.3. Time Recovery Function. The recovery time is defined as the period necessary to restore the functionality of a structure and infrastructure system to the desired level that can operate or provide a similar or better service than the initial function [53]. The time recovery function is used to express the complicated recovery process that is influenced by several variables such as time and spatial dimensions. The recovery functions that are used to establish the functionality curves are classified into three types: linear recovery function, trigonometry recovery function, and exponential recovery function. Figure 6 show the examples of linear recovery functionality curves, trigonometry recovery functionality curves, and exponential recovery functionality curves.

Different kind of recovery functions is adopted depending on the system and the social response. Equations (11)–(13) show the linear recovery function, trigonometry recover function, and exponential recovery function, respectively.

$$f_{\text{REC}}(t, T_{OE}, T_{\text{REC}}) = 1 - \left(\frac{1 - T_{OE}}{T_{\text{REC}}}\right), \tag{11}$$

$$f_{\text{REC}}(t) = 0.5. \left\{1 + \cos\left[\frac{\pi(t - t_{OE})}{T_{\text{REC}}}\right]\right\}, \tag{12}$$

$$f_{\text{REC}}(t) = \exp . \left[-(t - t_{OE})\frac{\ln(200)}{T_{\text{REC}}}\right], \tag{13}$$

where T_{OE} is the time of occurrence event with intensity I, T_{REC} is the recovery time after an event, t_{OE} is the time of earthquake occurred.

As explained by Cimellaro et al. the linear recovery function is generally adopted when there is no information of the social response. However, the trigonometry recovery function is adopted where the society response to a drastic event is initially slow whereas the exponential recovery function is used where the society response to an extreme event is fast driven by an initial inflow of resources and thus the rapidity of the recovery process decreases.

3.4. Resilience Index Evaluation. As defined by the International Strategy for Disaster Reduction (2004) [54], resilience is "the ability of a system, community, or society that is potentially exposed to hazards to adapt by resisting or modifying in order to establish and sustain an adequate level

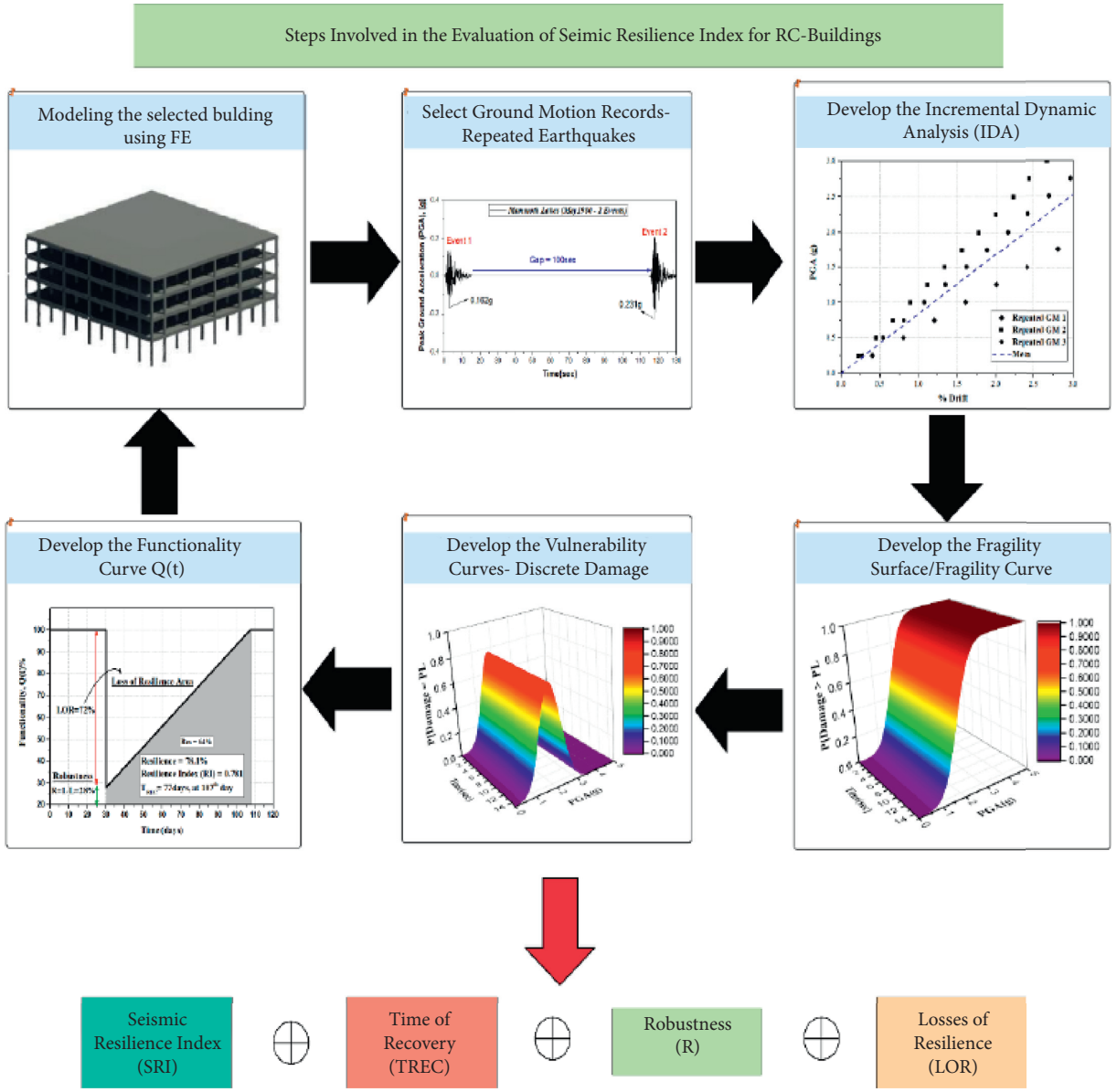

Figure 5: Framework steps for developing seismic resilience index (SRI) [50].

Table 4: Quantities or rates of depreciation for various types of buildings [51].

Rate of depreciation (%)	Type of building
5	Buildings that are utilized exclusively for residential purposes, with the exception of boarding houses and hotels, are referred to as residential premises. It is only when more than 66.66 percent of a building's built-up floor space is used for residential purposes that the structure is regarded to be used for residential purposes.
10	All other types of buildings do not belong into the category of residential buildings
100	Generally speaking, buildings are utilized for the installation of machinery and plants that are integral to the water treatment system and the water supply project. Furthermore, timber constructions and tin shelters are only intended to be temporary structures.

of reliability and functionality, which is determined by the degree to which a social system is capable of managing itself to raise this ability of lessons from previous disasters for better future preservation and to improve risk management."

Seismic resilience assessment can be qualitative or quantitative. According to Verrucci et al. [10], the selection of indicators is one of the critical factors in evaluating seismic resilience and has shown that qualitative assessment models tend to be more comprehensive than quantitative

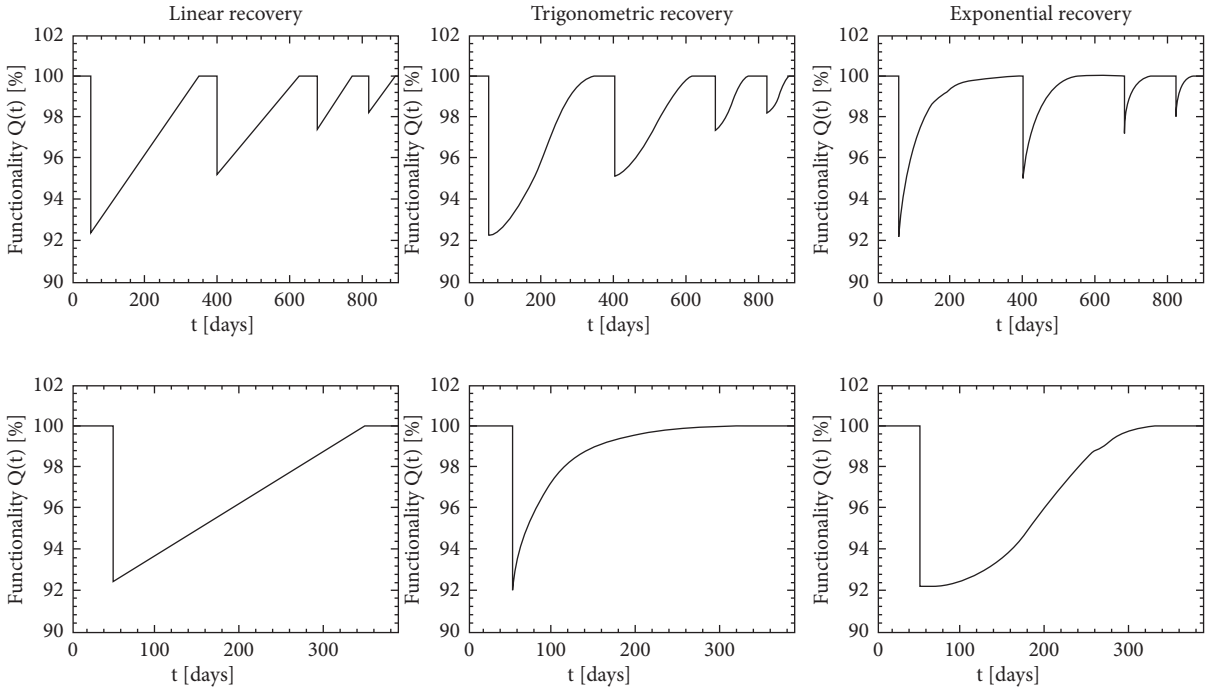

Figure 6: Examples of three types of functionality curves [53].

assessment models. The authors had reviewed previous models available in the literature and summarized a candidate set of indicators which categorized into five topical macro-areas. The topical macro-areas included planning and land-use, built-in resilience, continued functioning or redundancy, resources, and social cohesion.

Generally, the seismic resilience index is determined from the functionality curves with the aids of the fragility curves and/or the vulnerability curves. Although, it is important to note that, while the recovery progress is dependent on a variety of resources such as manpower and materials, the approach for quantifying the seismic resilience index is commonly written as (14) [8]:

$$R = \frac{1}{T_{LC}} \int_{t_{OE}}^{t_{OE}+T_{LC}} Q(t)\mathrm{d}t, \tag{14}$$

where, $Q(t)$ is the dimensionless percentile which is defined from the functional curve, T_{LC} is the control time interested which is the investigated time interval after an earthquake (usually considered to be 50 years for residential buildings) or the longest recovery time under the considered seismic intensities, and R is the resilience index.

3.5. Resilience Quantification Methods for Single Building. The concept of resilience is being implemented and defined according to several different perspectives which essentially explains the capability of a structure or a system to recover its functionality after an unexpected natural disaster such as earthquake, flood, fire, and landslides. From an engineering perspective, resilience is typically characterized as the ability of human societies to endure external disasters and to recover from such disasters [55]. In recent decades, several studies proposed frameworks that focused on the quantitative measures of disaster resilience after the different types of natural disasters. Engineering-related facilities and social-economic resilience were among the categories of catastrophe resilience that had gotten the most attention, particularly when it came to seismic resilience of structures. From in civil engineering perspective, the quantification of resilience consists of four parts: first, the assessment of resilience for an urban system which consists of physical elements (individual buildings, transportation systems, piping system, and other urban lifeline facilities) and non-physical elements (social, economic, and ecosystems); second, the quantifiable indicators of the resilience in infrastructures and disturbed networks; third, measures of building sub-system resiliency; and forth is the analysis of resilience limit state [56].

The resilience of a single building is described as the capacity of the building to endure shocks from external threats while also having the ability to recover its functionality after being damaged or destroyed. Bruneau et al. [57] studied structural resilience by identifying four primary characteristics. These characteristics are known as the 4R attributes: robustness, redundancy, rapidity, and resourcefulness. According to Lu et al. [56] there are two main existing methodologies for evaluating the resilience of single buildings: risk and resistance analysis of structures; and rating of structural resilience.

The first existing methodology is the risk and resistance analysis of a building by taking into account various hazards. The design phase and information for a hazard, such as the risk and design loadings, is often obtained based on the environmental conditions, the types of structural elements, the building materials, and the structure's geographic

information system (GIS) data. As a result, the design information is used to determine the structural resilience of the construction. According to this methodology, US Green Building Council had proposed the Leadership in Energy and Environmental Design (LEED) assessment and planning for resilience which a hazard assessment for the project site is a prerequisite of this assessment [58]. Besides, the Insurance Council of Australia (ICA) developed the Building Resilience Rating Tool (BRRT) based on this methodology [59]. The BRRT rates the resilience of the building by identifying the potential hazards the building is exposed to. Thus, an evaluation of the vulnerability based on the materials and the structural types of the building is performed.

The second method currently in use is the grading of structural resilience under a given hazard scenario. When a hazard is identified, the indicators relating to the 4R, as well as other properties of the structure, can be quantified, allowing the structure's resistance to be measured in terms of grades or star ratings. The Building Rating System proposed by the United States Resiliency Council (USRC) and the Resilience-Based Earthquake Design Initiative (REDi) Rating System proposed by [62] is the typical examples of this methodology. According to the USRC building rating system, the evaluation approach employed is based on either ASCE 41-06 (ASCE, 2007) or FEMA P-58; in contrast, the REDi building rating system utilized the methodology of FEMA P-58 without modification [56].

3.6. Recent Seismic Resilience Applications. In both civil and earthquake engineering, the assessment of seismic resilience is majorly applied to residential and commercial buildings. The types of buildings commonly chosen by the researchers have reinforced concrete buildings and steel frame structures. Moreover, masonry buildings and timber structures have also become the target of researchers in investigating the seismic performance of the buildings in the cities. The seismic resilience assessments for these major types of structures which had been performed and proposed in the earlier research are discussed in this review paper.

Asadi et al., [61] proposed a multi-criteria decision-making framework that is divided into three main modules: the System Concept and Criteria (SCC) module; the Resilience, Sustainability, and Energy Analysis (RSEA) module; and the Multi-Criteria Decision Making (MCDM) module. For the purposes of this study, the framework was applied to two different sets of archetypal reinforced concrete shear wall structures. To evaluate the seismic performance of the case studies, the following analysis was performed: incremental dynamic analysis, fragility analysis, loss estimation, recovery analysis, and resilience analysis. The authors highlighted that the key factors such as repair or construction cost, recovery time, injuries, fatalities, embodied energy, and operational energy shall be integrated to achieve a holistic framework. Furthermore, the findings of the study revealed that the proposed framework was more appropriate for use in assessing various design alternatives for low-rise to midrise residential or commercial structures.

Using structural reliability approaches, Sangaki et al. [62] created a probabilistic integrated framework that contained a collection of probabilistic models. The proposed framework was applied to a standard concrete framed structure in order to determine the seismic resilience index of the structure and, as a result, to develop a resilience curve. The methodology of the framework includes non-linear response history analysis, fragility analysis, functionality analysis, recovery analysis, and resilience analysis. With the proposed framework, the consideration of the impacts of an unlimited number of doubts has revealed as the most significant benefit of the proposed framework. Furthermore, it was asserted that the proposed framework was able to supply the capability of determining the probabilistic model of the resilience index as well as the development of resilience curves, both of which may be used in the resilience-based design (RBD) approach.

Sardari et al. [47] had evaluated the seismic resilience of a steel frame school building in Iran and examined the accuracy of the seismic index results by comparing two common methodologies of resiliency assessment and the resiliency parameters. The research study concentrated on the resiliency and reliability analysis of the steel frame buildings, therefore, the analysis involved included the non-linear time history analysis, the incremental dynamic analysis, the fragility analysis, the vulnerability analysis, loss estimation, and recovery analysis. Moreover, in order to evaluate the reliability of the frame structures, the First Order Reliability Method (FORM) and sampling method were adopted. In addition, several retrofitting techniques were proposed in the study, and the analysis of the efficiency of the retrofitting techniques was performed and compared to provide an additional reference for future study. The authors point out that retrieving resiliency measures via the use of vulnerability curves produces more truthful and reasonable findings than extracting resiliency indicators through the use of resilience curves.

Hosseinzadeh and Galal [63] had performed the seismic resilience assessment of reinforced masonry shear wall buildings with masonry boundary elements. When developing a numerical model for the research project, the fiber-based modeling approach was adopted. The accuracy of the numerical model was then verified by comparing the results of experimental and numerical hysteresis loops at different drift levels. The non-linear time history analysis was done on two sets of 44 far-field and near-field ground motion records. The procedures involved in the study include the incremental dynamic analysis (IDA), fragility analysis, development of variation of interstory drift, the development of story shear response plot, and the evaluation of seismic resilience. The authors compared the results of building with and without masonry boundary elements for both far-field records and near-field records. The outcomes of the assessment show that by utilizing the masonry boundary elements, the resiliency of the reinforced masonry shear wall building had effectively reduced the structural and nonstructural losses of the buildings and resulted in improving the resiliency of the buildings.

Avila-Haro et al. [64] had conducted a probabilistic seismic assessment of a high-rise unreinforced masonry building in Spain. The methodology of the framework includes modal and pushover analysis, non-linear static analysis, and fragility analysis. Thus, the damage index of the case study was derived from the fragility curves developed. However, the study also performed a comparison of the analysis result of buildings with and without a probabilistic approach. As an outcome of the probabilistic approach, the variability in the mechanical properties of the masonry had generated significant uncertainties in the seismic response of the case study which led to unexpected damage, compared to that of the approach without consideration of probabilistic nature.

Furthermore, the previous studies which concentrated on the assessment for these four major structural types: reinforced concrete frame structures, steel frame structures, masonry structures, and timber structures in the past few years had been summarized in Table 5.

4. Seismic Resilience of Community Infrastructures

In past decades, frameworks used to evaluate the seismic resiliency of other subsystems of a community such as hospitals, schools, bridges, and infrastructures have been proposed and introduced. The frameworks for the subsystems proposed and obtained in different countries in previous studies are discussed in the following section.

4.1. Frameworks for Hospital Systems. Hospital systems are recognized as critical systems in a community that plays an important role in disaster rescues. However, hospitals were inevitable to encounter the earthquake and lost their functionalities due to the impact of seismic events. Therefore, several studies had been conducted previously to propose an effective framework in evaluating the seismic resilience of the hospital systems. In summary, the frameworks adopted by previous studies have a major similarity in methodology except for the application of the indicators and parameters.

Hassan and Mahmoud [81] had proposed a framework for a six-stories high hospital which is assumed to be located in Memphis, Tennessee, United States. In the study, the functionality of the hospital comprised both quantity and quality portions. The quantity portion is indicated by three major components, namely space availability (including the accessibility, supportive infrastructures, and working space), personnel availability (staff and professionals), and supplies availability. The aforementioned components were the essential components that were required to ensure the hospital's operation. Meanwhile, the quality portion of the functionality of the hospital was represented by the satisfaction of the patients toward the provided medical services. Finally, the overall functionality of the hospital was evaluated by combining both the quantity and quality functionalities. Thus, the resiliency of the hospital was assessed graphically using the functionality curve plotted.

Yu et al. [3] provided a framework for assessing the seismic resilience of reinforced concrete frame urban hospitals in China that are designed in accordance with the Chinese seismic design code (GB 20011-2010). The framework is proposed by considering the importance of the critical roles of hospital systems; therefore, the seismic resiliency of the hospitals is indicated based on the damage states of the structural system, the number of casualties, the availabilities of the medical services, and also the economic losses. In the study, the fault tree analysis (FTA) is adopted to investigate the effect of the interdependencies such as damage of the nonstructural elements on the functionality of the medical equipment. The results claimed that the assessment results be more realistic with the application of fault tree analysis (FTA). There were three types of repair strategies used in the recovery phase of the study, namely parallel repair strategy, serial repair strategy, and REDi method. The results show that the recovery period required by the case study varies with the selection of repair strategy.

Shang et al. [16] also introduced a quantitative framework to assess the seismic resilience of the hospital systems in China that was designed based on the Chinese seismic design code (GB 20011-2010). The framework considered the seven essential sub-systems of the hospital, namely structural system, electrical system, mechanical system, water supply, and drainage system, medical system, egress system, and architectural system. In addition, each of the subsystems was rated and scaled depending on their importance toward the hospital systems and their contribution toward the degree of damage of the hospital systems. Throughout the framework, an idealized repair sequence for the subsystems was suggested by the authors to recover the emergency functionality of the hospital systems.

Niazi et al. [85] had performed an assessment of the seismic resilience index of the hospital in Tehran, Iran. Due to the case study itself being able to supply the water and electricity for the hospital in emergency states, therefore, the impact of the disturbances in water and power supply were neglected in the study. The major parameter indicating the functionality of the hospital was the patient waiting window which was influenced by the availability of the hospital staff and the medical services. The admission rate of patients entering the emergency department was evaluated through a demand model to represent the patient waiting time. The functionality of the hospital was expressed as the ratio of the total number of the functional emergency ward to all units that provide proper services without a reduction in performance. Thus, the resiliency of the hospital was evaluated through the functionality curve.

4.2. Frameworks for Bridges. Bridges are a crucial component of the transportation network in a community from decades ago. The exposure of the bridges to a natural disaster will give a significant impact on social losses and economic losses. Therefore, the seismic performance of the aging bridges has taken the attention of the communities.

Andrić and Lu [86] had evaluated the seismic resiliency of the bridge located in California, United States. The fuzzy

Table 5: Seismic resilience case studies applications on different building typology.

Author	Methodology	Type of structure
Bu et al. [65]	Incremental dynamic analysis, fragility analysis	Steel frames with steel slit shear walls
Chen and Bai [66]	Nonlinear static analysis, nonlinear dynamic analysis, damage index assessment	Buckling-restrained braced reinforced concrete frames
Estrella et al. [67]	Nonlinear static and dynamic analysis	Timber buildings with wood-frame shear walls
Hassan et al. [68]	Nonlinear response history analysis, incremental dynamic analysis, fragility analysis, vulnerability analysis, resilience assessment	Steel-reinforced concrete (SRC) composite column buildings
Hejazi and Jalaeefar [69]	Incremental dynamic analysis, fragility analysis, risk analysis, resilience analysis	Infilled special steel moment-resisting frames
Hosseinzadeh and Galal [70]	Nonlinear dynamic analysis, fragility analysis, loss estimation, recovery analysis, resilience analysis, Monte Carlo simulation, sensitivity analysis	Reinforced masonry shear wall system with boundary elements
Jiménez et al. [71]	Vulnerability index method (VIM)	Hybrid timber-masonry buildings
Mohammadi et al. [72]	Incremental dynamic analysis, fragility analysis	Infilled steel frame structures
Vona et al. [73]	Fragility analysis, vulnerability analysis, resilience analysis	Reinforced concrete buildings
Yun and Chao [74]	Experimental test, development of hysteresis curve and skeleton curve, residual deformation, energy dissipation, validation of earthquake resilience	Prefabricated self-centering steel frame
Zhu et al. [75]	Nonlinear static pushover analysis, fragility analysis, risk assessment	Steel moment-resisting frames with self-centering viscous-hysteretic devices
Anwar and Dong [76]	Fragility analysis, recovery analysis, functionality analysis, resilience analysis	Retrofitted reinforced concrete buildings
Anwar et al. [77]	Hazard analysis, structural analysis, damage analysis, seismic risk assessment, seismic sustainability, and resilience assessment	Reinforced concrete structures
Fang et al. [78]	Nonlinear response history analysis, vulnerability analysis, resilience analysis	Self-centering steel frames with SMA-viscoelastic hybrid braces
Giordano et al. [79]	Vulnerability analysis	Unreinforced masonry schools
Xu et al. [80]	Loss estimation, fragility analysis, functionality analysis, resilience analysis	Six-story reinforced concrete frame building

framework used in the study comprises the seismic hazard analysis, bridge fragility analysis, and seismic resilience assessment. The residual functionality of the bridge was assessed by investigating the relationship between the bridge damage and the functionality based on the data collected (expert's opinion and expert's subjective judgment of the expected level of traffic capacity). Thus, the recovery period required was calculated by mathematical expressions for the membership functions. A similar framework was also obtained by Dong and Frangopol [84] to evaluate the seismic risk and resilience of highway bridges in California.

Huang and Huang [85] had introduced a resilience framework for the reinforced concrete bridges which exposed to the earthquake. The framework comprises of physical vulnerability model, restoration model, and resilience analysis. The physical vulnerability model was used to obtain the damage probabilities of the bridge piers whereas the restoration model was used to evaluate the functionality of the aging bridges. In the study, the seismic performance of the bridge piers was evaluated by considering the impact of the corrosion of main reinforcements, the cracking of the concrete covers, and the degradation of the bond strength between reinforcements and concrete.

Sun et al. [86] had examined the seismic resiliency of the road network across the Luchon Valley, France by proposing an agent-based modeling framework. In the study, the critical bridges of the road networks were chosen to represent the resilience of the road network under earthquake scenarios. The damage level of each of the single bridges was determined by the fragility analysis. Thus, the long-term functional recovery of the bridges was driven by three agents which have different attributes of the traveling speed and efficiency. Finally, the seismic resilience of the whole road network was indicated by the integration of the total functional bridges to the recovery time required.

4.3. Frameworks for Water Supply Systems. Water is one of the indispensable natural elements to all livings. The failure of water supply not only impacts the residents and critical consumers but also impacts other infrastructures and services. Therefore, the functionality of the water supply systems in the communities in the aftermath of natural disasters such as earthquakes had attracted the attention of the government and the community.

Balaei et al. [87] had examined the robustness of the water system in Pukerua Bay which is located in Wellington, New Zealand. The damage degree of the buried pipelines of the water system due to the slope failure and the fault rupture was measured. The robustness of the water system was analyzed as a ratio of the product of the robustness and the length of functional subsectors to the total length of the subsectors.

Liu et al. [88] had performed an assessment of seismic resilience for water distribution systems in Mianzhu, China. The performance levels of the water distribution systems in the daily operation state were indicated depending on the degree of satisfaction of consumers which is indicated by consumer nodes toward the water served. In the study, the satisfaction degree of the consumers was obtained through the flow analysis method which considered the time-dependent water demand. Moreover, the study was focused on the recovery of the buried pipes which play the most critical part in a water distribution system. Therefore, the study analyzed the degree of damage of the buried pipes by proposing a pipe recovery model which included three important aspects such as joint seismic reliability, pipe seismic reliability, and pipe damage number. The recovery period required evaluated by the framework can be influenced by three critical factors, namely recovery resources, recovery method, and recovery sequence.

4.4. Frameworks for Electric Power Systems. In the modern era, most of the infrastructures, structures, and human beings rely on the electric power distribution networks to provide and support the daily essential services to the whole community. Power distribution systems play a crucial role to generate and transmit the electrical to the consumers at various locations. Consequently, the functionality of the power distribution system to support daily services and activities had become the focus of the government and the community.

Fotouhi et al. [89] had introduced a model applied to the coupled electric power-traffic system in Minneapolis, Minnesota, United States, to quantify the resilience of the coupled system. In the study, the components considered will contribute the damage toward the whole system including the substations, the traffic signals, the roadway links, and the transmission lines. Thus, the damage levels of the aforementioned components under the scenarios were indicated in two scales: functional and damaged. During the repair phases, the recovery degree of the networks was varying with the levels of budgets and the repair options adopted. As a result, the resilience levels of the networks under restricted repair and recovery opportunities were evaluated and presented.

Cho et al. [90] had conducted an experimental study to investigate the seismic resilience of the enhancement applied for the piping system of a nuclear power plant in Fukushima, Japan. The enhancement tool used in the experiment was the steel coil damper which claimed to improve the seismic safety of the piping systems by accommodating the thermal transformation of the piping supports. The seismic resiliency of the enhanced piping systems was assessed throughout the dynamic response analysis.

Cardoni et al. [91] proposed a methodology to evaluate the resilience of the power distribution networks in Italy. The Similarities Design Method and the Density Design Method are the two most important components of this technique. The resiliency of the power distribution networks was expressed as a ratio of the return period of the seismic event to the number of consumers with no power supply. In the study, a new indicator called the Power Resilience Index (PRI) was established, which was defined as the integration of transformer restoration rate, network robustness, and the presence of alternate functional lines. According to the scientists and the authors, PRI was capable of measuring the early resilience conditions of the networks. Meanwhile, the recovery time for the substations of the networks was determined by either taking into account solely the transformers' recovery time or by using data that was readily available.

4.5. Compilation of Infrastructure Resilience Framework Applications. Other than the aforementioned frameworks for those sub-systems, there are still many frameworks being proposed and introduced for the sub-systems of a community in the past centuries in different countries. Table 6 summarizes the recent frameworks proposed.

5. Summary

Earthquake excitation is considered as a complex loading to a structure. Fundamentally, the seismic performance of the structures can be evaluated by the seismic resilience index, the damage index, and the seismic vulnerability index. Each of the assessments has its advantages and drawbacks. Some may be time-consuming with precise results, and some may be simple and speed with limitations in the interpretation of results. It is essential to select the appropriate assessment by considering the availability of the collection of the data required by each assessment and the availability of the equipment required if any.

One of the essential goals of the evaluation of the seismic resilience index of the structures is to introduce or propose the repair strategy or the retrofitting techniques. With the aids of the functionality curves, the repair strategy or the retrofitting techniques can be proposed or introduced effectively based on the recovery time and the resilience assessment results. Apart from the implementation of the design codes which consider the seismic effect in the design such as Eurocode 8, various novel building damage evaluation techniques and retrofitting tactics offer a variety of options that can be employed to improve or accelerate the recovery process's functionality. Compared to constructing a new building with a similar purpose or service, retrofitting a damaged structure is often more cost-effective. Retrofitting process is a general term that consists of various treatments such as preservation, rehabilitation, restoration, and reconstruction [110].

Retrofitting process with respect to seismic consideration is usually applied on the existing buildings which potentially subjected to the seismic excitation to extend their serviceability, to improve the sustainability of the buildings, and to maintain or improve the seismic safety of the building. Hence, selecting the appropriate retrofitting method must be determined depending on the project or structure objectives. Commonly, the decision-makers, designers, or stakeholders prefer to choose the retrofitting

Table 6: Seismic resilience frameworks for sub-systems of the community.

Author	Framework	Methodology	System	Location
Ferrario et al. [92]	Seismic risk and resilience	Seismic hazard analysis, functionality analysis, recovery analysis, analysis of topological measures	Electrical power networks	Chile
Iannacone et al. [93]	Seismic resilience	Reliability analysis, functionality analysis, recovery analysis, resilience analysis	Potable water infrastructure	USA
Ahmadi et al. [94]	Resilience index	Adaptability analysis, absorbability analysis, recovery analysis	Energy systems	—
Cardoni et al. [95]	Seismic vulnerability and resilience	Seismic analysis, damage assessment, vulnerability analysis, resilience assessment	Urban telecommunication network	—
ChienKuo et al. [96]	Seismic resilience	Reliability analysis, resilience analysis	Bridge (retrofitted through reinforced concrete jacking)	Taiwan
Katayama et al. [49]	Seismic diversity and robustness	Fault tree analysis (FTA), inter-period correlation	Nuclear power plants	Japan
Ramezanpour et al. [97]	Damage index and seismic resilience	Ductility analysis, damage analysis, resilience analysis	Stabilized or un-stabilized rammed earth walls	—
Xiao et al. [98]	Seismic resilience	Fragility analysis, Monte Carlo simulation, recovery analysis	Power-natural gas lifeline networks	—
Zhai et al. [99]	Physical-organizational method for functionality assessment	Structural analysis, damage analysis, availability analysis, the arrival of patients, functionality analysis	Hospital	China
Zong et al. [100]	Seismic resilience index	Three-stages resilience enhancement (pre-earthquake network enhancement, postearthquake pipeline pressure tests, postearthquake pipeline repairs), resilience analysis	Gas distribution networks	China
Capacci and Biondini [101]	Seismic resilience index	Fragility analysis, functionality analysis, recovery analysis	Bridge networks	—
Chen and Li [102]	Seismic response	Seismic analysis (shear deformation, drift, displacement, and overturning Stability)	Tall pier bridges (retrofitted with lead rubber bearings and rocking foundation)	China
Eghbali et al. [103]	Seismic resilience index	Retrofitting operations monitoring, functionality analysis, recovery analysis	Schools	Iran
Koc et al. [104]	Comprehensive resilience assessment (CRAFT)	Hazard characterization, damage assessment, transportation system analysis	Transportation systems	Loss angeles
Li et al. [105]	Seismic resilience index	Fragility analysis, functionality analysis, recovery analysis	Electrical substation system	China
Rezaei Ranjbar and Naderpour [106]	Seismic resilience index	IDA, fragility analysis, vulnerability analysis, loss estimation, functionality analysis, resilience analysis	Hospital	Loss angeles
Kilanitis and Sextos [107]	Seismic risk and resilience	Seismic hazard analysis, fragility analysis, recovery analysis	Roadway networks	—
Tong et al. [108]	Seismic resilience	Experimental analysis, numerical modeling	Prestressed precast segmental bridge piers reinforced with high-strength bar	—
Hassan et al. [68]	Interdependent functionality reduction framework	Fragility analysis, direct losses, functionality analysis	Hospital	USA
Nan and Sansavini [109]	Resilience of interdependent infrastructures	Development of an integrated resilience metric, multi-layer hybrid modeling approach (screening analysis, individual model development, model interaction)	Infrastructures (electronic performance support systems)	Switzerland
Cimellaro et al. [9]	Disaster resilience	Loss function, simplified recovery function models, mechanical analogy, fragility analysis	Hospital	Southern California

strategy with the maximum resiliency and the minimum cost required. To investigate the effectiveness and also the appropriate degree of the selected retrofitting technique, it is suggested to perform the seismic resilience assessment by modeling the retrofitted structures. In order to preserve economic activities, the retrofitting plan must achieve three primary objectives: reduction of seismic damage, reduction of recovery time, and reduction or annulment of downtime or disruption of business operations [73]. As a result, the best and most appropriate retrofitting strategy has the lowest possibility of causing a complete collapse damage condition and the highest possibility of causing a fully operational state.

Other than the resiliency of a single structure or building, the concept of community resilience can be adopted as a useful tool for decision-makers in disaster or risk management and mitigation strategies planning. In order to improve the effectiveness of the evaluation of the resilience of communities, the resiliency of each subsystem of a community with consideration of their uncertainty is defined and considered in multi-disciplinary and multi-criteria methodologies. In addition, Vona et al. [29] highlighted that a global community resilience model must be long-term validated and contingent on the most vulnerable and low resilient parts of the community. Furthermore, compared to previously existing approaches that evaluate resilience based on both the technical and economical characteristics, the new resilience model also evaluated the community resilience based on the organizational and social aspects.

Based on the considerations taken in the development of the new resilience model, the repair time and final functionality level are influenced by the entire seismic damages and losses. Not only that, but the reconstruction procedure as well as the accessible economic ability are also taken into consideration. In addition, the approval process for funding and financial support applications takes a significant amount of time. Thus, considering the period for approval of financial supports into the reconstruction process will improve the accuracy and the resiliency of the community. [108].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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