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Resilience and Sustainability in Seismic Performance Assessment: A Review

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Abstract

This paper provides a summary of the literature in the past twelve years that focused on life cycle seismic performance of buildings and bridges, considering metrics related to both resilience and sustainability. The studies were presented and discussed in terms of the following categories: 1) individual buildings, 2) portfolio-scale assessments of buildings, 3) seismic retrofit of buildings, 4) bridges (individual and network), 5) methods for jointly assessing resilience and sustainability in life cycle performance assessment and 6) optimization for resilience and sustainability. Several of the considered studies focused on issues that belong to multiple categories (e.g., optimizing seismic retrofit of building portfolios) and are therefore discussed in multiple sections. The methodology used to review the existing literature is also presented along with the geographic distribution of the authors and publication timelines. Given the acute focus in recent years on climate resilience, we expect that research in this area will continue to grow in popularity.

Keywords

Earthquakes, Sustainability, Climate Change, Performance-Based Engineering, Life Cycle Analysis

1. Introduction

Resilience and sustainability are two key related concepts that are relevant to the seismic design and performance assessment of the built environment. Resilience is often defined as the ability of a system to withstand some external disruption (e.g., due to an earthquake), recover functionality in a timely manner and adapt to the new circumstances following the disruption [1] [2]. On the other hand, sustainability of the built environment addresses concerns related to resource consumption and environmental and social impacts [3]. The life cycle of any infrastructure system comprises several stages, including product acquisition, construction, use and end-of-life stages [4]. All stages of this life cycle require resources (e.g., energy) and also produce environmental emissions (e.g., CO_2). A sustainable system is one that is able to minimize the resource consumption and environmental impacts over its life cycle. During the use phase, which can last anywhere from 50 to more than 100 years, an infrastructure system can be exposed to multiple earthquake events. A seismically resilient system is one that can minimize the damage caused by these earthquakes. In doing so, the resource consumption and environmental emissions associated with repairing and replacing the damage caused by an earthquake, are also minimized. In other words, an infrastructure system that is seismically resilient is also sustainable.

There have been numerous studies on the intersection between resilience, sustainability and the seismic performance of building systems. These studies have very differing points of focus. For example, some studies address the resilience and sustainability of individual buildings [5], whereas others are focused on building inventories [6]-[8]. Whereas most of the studies are focused on the resilience and sustainability of buildings [5] [7], there are a few studies that addressed individual bridges or bridge networks [9] [10]. Another category of studies is those that try to optimize resilience and sustainability over the life cycle (e.g., [11]).

This paper provides a review of the existing literature on the seismic resilience and sustainability of the built environment. By performing a thorough review of the literature on this topic, this study sheds light on those sub-topics that have been well-studied as well as those that require additional research. The rest of the paper is organized as follows. The next section presents the methodology that is used for the review including the sources of the literature as well as the criteria used to search for relevant studies. Then, the results from the review are presented in terms of the type of infrastructure (*i.e.*, buildings versus bridges), the scale of the assessment (*i.e.*, individual versus inventory), the seismic design of new systems versus the retrofit of existing ones, and studies that attempt to optimize life cycle performance for resilience and sustainability. The study concludes with a summary of key findings and suggestions for future related work.

2. Methodology

The primary source of the literature search was Google Scholar. We began by conducting a search using the following keywords (entered all at once): resilience, sustainability, seismic and earthquake. The initial search focused on the most recent studies where only papers published in 2020 and 2024 were considered. Based on the initial search, we excluded those papers were found to only focus on seismic only (*i.e.*, resilience and sustainability not considered), sustainability only (*i.e.*, seismic and resilience not considered), and resilience only (*i.e.*, seismic and sustainability not considered). We also disregarded studies focused on multihazard resilience and sustainability where earthquakes and some other hazards (e.g., tsunami) were considered. Emphasis was placed on studies that focused on engineering analysis and modeling. In other words, policy and opinion papers were filtered out of the initial search.

The only two types of infrastructure that were considered were buildings and bridges. Therefore, papers that focused on other distributed infrastructure such as water and power sustains were not included in the review. There were many papers that focused on either resilience-based seismic performance or life cycle environmental performance. However, only papers that considered both seismic resilience and sustainability-based assessment were included in the review. The considered studies were not limited to any geographic location so multiple regions around the world were represented. However, as shown in **Figure 1** below, most of the studies that came out of the search were conducted or based in North America.

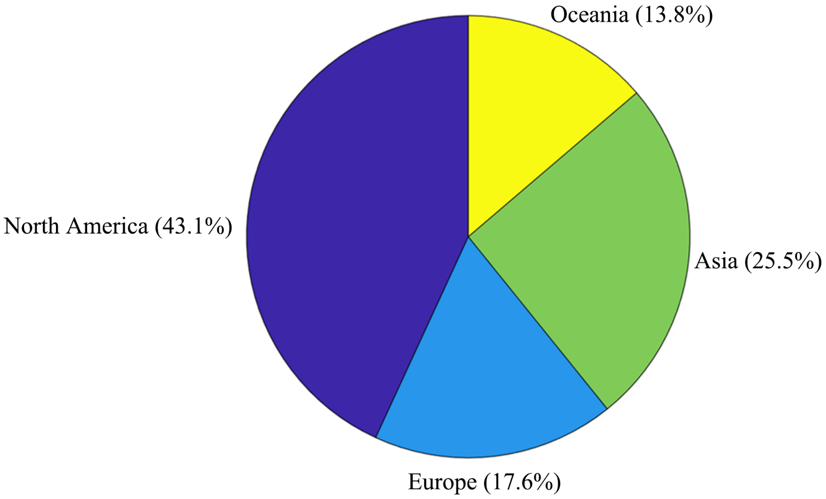

Figure 1. Pie chart distribution of where studies were conducted based on the continent (North, South and Central America, Europe, Asia and Africa).

Based on the initial search considering only 2020 and 2024, 9 papers were found. After analyzing and filtering the unwanted papers from this initial set, the search was extended to studies conducted prior to 2020. The source of these earlier (pre-2020) studies included both Google Scholar as well as references from the 2020 to 2024 papers. This extended review produced an additional 25 papers published prior to 2020. The literature search only extended as far back as 2011. In other words, studies published more than 13 years ago were not considered in the review.

After all of the papers were assembled, they were grouped based on the following categories: 1) building-specific versus building inventory, 2) bridges (individual and inventory), 3) new buildings versus retrofit existing buildings, 4) methods for jointly assessing resilience, sustainability and seismic performance and 5) optimizing seismic design for resilience and sustainability. **Figure 2** below shows a bar chart with the number of papers published each year between 2011 and 2024. Almost a half of the papers were published between 2015 and 2018 and approximately 20% were published between 2021 and 2024.

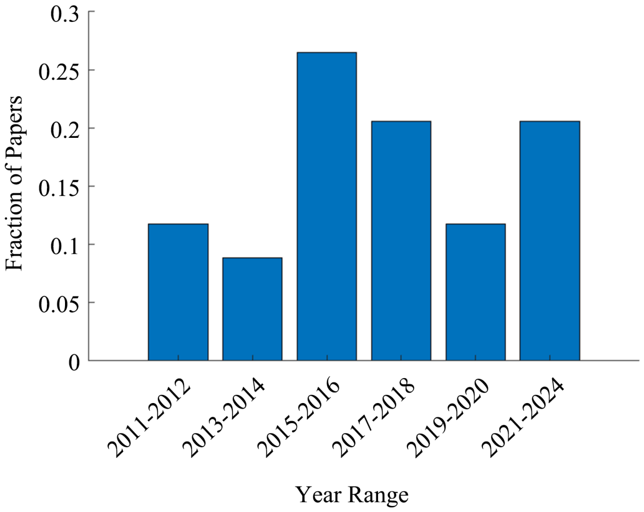

Figure 2. Number of publications per year and distribution among the considered categories.

3. Results

3.1. Individual Building Assessments

Resilience and sustainability in the context of seismic life cycle analysis can be quantified for inventories or individual buildings. This section focuses on the latter of the two. Building-specific life cycle seismic performance assessments can be performed when designing a new building [12] or evaluating/retrofitting an existing one [13]. Some studies focus on specific types of lateral force-resisting systems (e.g., [14]) while others focus more on developing a methodological framework that can be applied to any type of system. In the design context, some studies focus on life cycle optimization which is discussed later in the paper.

A study by Zhao *et al.* [15] developed a methodology to consider performance-based design and life cycle assessment in the development of sustainable structures. The study provides a discussion on the implications of the framework to engineering practice. The framework was applied to evaluate the performance of the Lvyue Building in Beijing, China. Park *et al.* [12] developed a comprehensive sustainable seismic analysis model to study the relationship between carbon dioxide emissions, seismic performance, and material production costs in building seismic design schemes. The methodology was applied to 4- and 10-story reinforced concrete frame buildings. Another study by Huang and Simonen [13] conducted a comparative environmental analysis of seismic damage in buildings. The study utilized the Performance Assessment Calculation Tool (PACT) developed by the United States Federal Emergency Management Agency (FEMA). The study found that non-structural building components such as the enclosure, interior finishes, heating, ventilation, and air conditioning (HVAC) contribute significantly to the environmental impact caused by earthquake damage. An earlier similar study was conducted by one of the two authors of the aforementioned paper [18].

Genturk *et al.* [19] developed a life cycle sustainability assessment (LCSA) framework for studying the performance of reinforced concrete buildings during earthquakes. The building's sustainability at different stages of its service life is quantified in terms of economic, environmental and social metrics. Dong and Frangopol [14] demonstrated the superiority of base-isolated steel buildings by comparing their life cycle performance with conventional systems. Their performance was comparatively assessed by considering the following three "pillars of sustainability": economic, environmental and social. Studies by Asadi *et al.* [5] [20] utilized risk-based multi-attribute utility theory and analytic hierarchy processes to develop a multi-criteria decision-making framework to assess building life cycle performance. The framework considers economic, social and environmental criteria in building design. The method is used to seismically design a series of reinforced concrete shear wall buildings.

The building-specific life-cycle performance assessment studies are by far the most popular of the categories presented in this review. In addition to the papers discussed earlier, numerous other studies that fall into this category have been conducted (e.g., [21]-[29]).

3.2. Assessment of Building Inventories

As mentioned earlier, most of the prior studies that examined the implications of seismic performance assessment to resilience and sustainability focused on individual buildings. However, there are a few studies that addressed issues related to building inventory or portfolios. These studies can be placed into two categories. One category focusses on real events by trying to quantify the economic, environmental and social impacts of historical earthquakes (e.g., [6]). The other category of studies uses simulation models to quantify the resilience and sustainability of building inventories based on hypothetical or simulated events.

In a paper by Zhou *et al.* [8], a set of indicators, an assessment method and an optimization routine is established to evaluate building performance at the inventory scale. The performance indicators include economic loss, downtime and environmental impact (specifically, CO_2 emissions). The performance-based assessment methodology is used to quantify the impact in terms of the various metrics. The details of the optimization are discussed later in the paper in the subsection that deals with "optimizing for resilience and sustainability". The framework is used to evaluate the implication of retrofit alternatives for different buildings in the community. This study would be under the category of "simulation-based" assessment *i.e.*, relies on hypothetical earthquake scenarios.

Kavvada *et al.* [7] developed a framework that quantifies the relationship between seismic retrofit activities and their implications to economic, environmental and equity-based performance metrics. The simulation-based framework was implemented on a building inventory located in the City of San Franciso. The part of the framework that involves bi-objective optimization is discussed later in the paper (in the " optimizing for resilience and sustainability" section). The framework allows modelers to examine the complementary and competing aspects of equity and economic efficiency.

A study by Gonzalez *et al.* [6] is the only one that considers the resilience and sustainability implications of a real earthquake. Specifically, the authors investigate the demolition actions of Christchurch during the 2010/2011 Canterbury, New Zealand earthquake, quantifying the implicit carbon and energy costs. The considered inventory comprises 142 reinforced concrete buildings demolished after the earthquake. The global warming potential of the demolished buildings was assessed in terms of the embodied CO_2, the energy associated with the building materials, and the impacts of the construction and waste removal processes. The results indicate that the demolition of the set of reinforced concrete buildings had extremely high environmental costs and included the production of additional waste and pollution.

3.3. Bridges (Individual and Inventory)

Most of the studies considered in this paper are focused on buildings. However, there are a few studies that addressed the resilience and sustainability of bridges in the context of earthquake performance assessment. Mackie *et al.* [30] developed a probabilistic carbon accounting methodology for bridge repairs triggered by earthquake damage. The methodology was applied to a set of multi-span reinforced concrete highway overpass bridges in California. The study also compared the bridge performance groups and material quantities that dominated the seismic performance when quantified in terms of economic costs versus environmental impacts. The study by Tapia *et al.* [10] focused on seismically vulnerable bridges subjected to age-based deterioration. The life cycle cost, embodied energy and CO_2 emissions were compared in the life cycle assessment of aging bridges. A multi-span simply supported bridge was used for the case study. The authors propose that the framework be used to guide the selection of optimal rehabilitation strategies for aging seismically vulnerable bridges. The paper by Padgett and Li [31] developed a methodology for risk-based assessment of the sustainability of structural design. This is applicable (and was demonstrated) to both buildings and bridges. The results of the case study applied to both buildings and bridges underscored the potential tradeoffs between upfront cost and service life sustainability.

In general, the methods used to assess the resilience and sustainability performance of bridges are generally the same as for buildings. The key differences between the two are in the type of components that need to be considered and the effect of aging. For buildings, both structural and non-structural components can be considered in the assessment. Whereas for bridges, non-structural components is generally not a consideration. Also, for buildings, aging is generally not a major issue because the structural components are usually not exposed to the atmosphere. On the other hand, as discussed in Tapia *et al.* [10], age-based deterioration is a major concern for bridges because their structural components are more often exposed.

3.4. Seismic Retrofit of Existing Buildings

As discussed earlier, life cycle seismic performance with consideration of resilience and sustainability can be used in the context of new building design or existing building retrofit. The latter is addressed in this subsection. In this regard, Chiu *et al.* [32] argued that financial and environmental benefits should be considered (in addition to safety) in seismic retrofit design. To support their argument, the authors quantified the environmental and financial benefits of retrofit investments for reinforced concrete buildings. The case study focused on 16 seismic retrofit projects in Taipei, Taiwan region. Another study by Clemett *et al.* [33] [34] focused on determining the optimal seismic and energy efficiency for existing buildings in Italy. The PBEE framework was combined with life cycle analysis to quantify building performance using the "three pillars of sustainability". They also used multi-criteria decision-making to evaluate the optimal combination of seismic and energy retrofitting schemes, considering different combinations of seismicity and climatic conditions.

The study by Zhou *et al.* [8] was discussed in the section on building inventory assessment. Recall that this work focused on determining the optimal retrofit strategy for individual buildings within a portfolio. The bi-objective optimization routine considered risk, downtime and sustainability performance indicators in their assessment. Monte Carlo simulation was also utilized to consider different sources of uncertainty. The bi-objective optimization produced a set of Pareto-optimal retrofit solutions. Ribakov *et al.* [13] investigated the effectiveness of adding stiff diaphragms, high-damping rubber bearings or seismic isolation as retrofit solutions for reinforced concrete frame buildings. The results of the case study showed that the seismic isolation strategy reduction earthquake-induced damage by more than three times what was achieved for the high-damping rubber bearings. Belleri and Marini [35] developed a framework to quantify the influence of seismic events on environmental impact. The framework was used to determine the extent to which energy and seismic retrofit improved the overall life cycle performance of existing buildings.

3.5. Methods for Jointly Assessing Resilience, Sustainability and Seismic Performance

The seismic performance of a built system is assessed by evaluating the extent to which the earthquake shaking causes physical damage. There are several approaches to evaluating the seismic performance of infrastructure. The most sophisticated and explicit approach involves constructing detailed structural models of the system under consideration, subjecting it to earthquake ground motions, measuring the response and converting the response measurements to physical damage. The performance-based earthquake engineering (PBEE) methodology [36] provides a systematic and probabilistic approach to doing such an evaluation.

The framework is modular, such that the various steps (hazard characterization, structural analysis and damage assessment) can be performed individually and sequentially. Several of the studies in the previous and following subsections utilize some or all of the PBEE framework (e.g., [12] [17]).

The abovementioned performance assessment strategy requires significant computation and human resources. For example, construction and analyzing a building nonlinear structural model is a very time-consuming endeavor. It also requires a level of expertise and knowledge that is not ubiquitous across different civil and environmental engineering subdisciplines. An alternative to this detailed approach is the use of system-level fragility functions that relate the ground shaking intensity to an overall level of damage to the system. These fragility functions are able to circumvent the need for detailed structural modeling and analyses by directly linking the shaking intensity to system-level damage. This approach is often used in regional studies that involve hundreds or thousands of buildings or bridges (e.g., [7] [37]).

Once the performance of the system has been quantified using one of the abovementioned methods, the resilience and/or sustainability can be assessed. The resilience-based assessment seeks to quantify the level of functionality disruption to the system and the path to restoring that functionality over time (e.g., [1] [38]-[40]).

The sustainability assessments seek to quantify the resource (e.g., energy) consumption and or environmental emissions (e.g., greenhouse gases) that are associated with different phases of the built system's life cycle (material production, construction, use phase, removal and reuse). Seismic performance typically has implications to the use, material production and construction phases. For the use phase, the seismic performance will dictate how often and how much the system has to be repaired or replaced because of earthquake damage. The implication to the material production and construction phases is related to the fact that enhanced seismic performance typically requires more materials that are used in the construction and therefore, great resource consumption and emissions. However, these added resources and emissions are offset during the use phase because the earthquake-induced repair and replacement impacts will be reduced. There are four main approaches that have been used to quantify environmental sustainability of infrastructure systems: 1) environmental input-output life cycle assessment (EIO-LCA) [4], 2) process-based LCA [41], 3) hybrid (EIO + process-based) [42], and 4) environmental product declaration-based (EPD-based) [43] approaches.

The joint assessment of seismic performance, resilience and sustainability, is typically done within a life cycle framework. Meaning, the implications of these different performance metrics are examined for the different stages of the system life cycle. The material production and construction phases is when the system is designed and constructed. During the design process, there is often a tradeoff between the greater use of materials and processes which leads to more environmental impact and the enhancement of resilience and sustainability during the use phase. These life cycle assessments are often performed using probabilistic approaches that consider the uncertainty in the hazard (*i.e.*, earthquake occurrence rate and intensity of shaking), the damage and the consequences of that damage in terms of economic, social or environmental impacts. The next subsection discusses design optimization for resilience and sustainability which requires the joint or integrated evaluation presented in this section.

3.6. Optimizing for Resilience and Sustainability

As discussed earlier, there are both complimentary and competing aspects of resilience and sustainability. On the one hand, enhancing seismic resilience sometimes requires additional materials that can increase upfront costs and environmental impacts. However, these upfront economic and environmental costs are offset by the reduction in earthquake-induced damage and subsequent repairs during the service life of the building. Optimization is often used to carefully consider the tradeoffs within a life cycle analysis context. Relatedly, a study by Burton *et al.* [12] sought to evaluate the seismic performance of a 6-story controlled rocking braced frame (CRSBF) and determine the optimal design parameters that would minimize the combined upfront costs and seismically-induced economic losses and environmental impacts. The parameters considered in the optimization routine included the dead load on the rocking frame, the initial post-tensioning force, the fuse strength, and the aspect ratio. The optimization was performed using basic gradient-based methods. Similarly, Anwar *et al.* [11] optimized the community-level resilience and sustainability of a seismic retrofit program. The study integrated PBEE with multi-objective optimization techniques to consider the optimal balance between cost, resilience and sustainability. The study by Zhou *et al.* [8] has been discussed in two previous sections (*i.e.*, retrofit and inventory-based assessment). In this section, we will focus on the adopted optimization routine. Specifically, the study utilized non-dominated sorting and a crowding distance genetic algorithm to select the optimal solution in a randomly generated population.

The aforementioned optimization studies are particularly effective for demonstrating the synergies and tradeoffs between resilience and sustainability. For example, in the Burton *et al.* [12] study, the fuse yield strength was generally found to be negatively correlated with life cycle costs but positively correlated with life cycle CO_2 emissions. Moreover, the Zhou *et al.* [8] study found some retrofit programs provided more enhancements in terms of sustainability compared to resilience. Specifically, the $20 million (U.S. Dollars) retrofit program reduced downtime (proxy for resilience) and environmental impact (sustainability metric) by 32.59% and 50%, respectively.

4. Conclusion

In recent years, resilience and sustainability have been considered as important performance metrics in the seismic performance assessment of the built environment. Resilience is concerned with the ability of a system to withstand external shocks (earthquakes in this study), adapt to the changes that result from that shock, and recovery in a timely manner. Whereas sustainability is concerned with the efficient utilization of resources in the different phases of a system's life cycle. The joint consideration of these two categories of performance metrics is important because there are tradeoffs between them. This study provided a summary of the existing literature on the intersection between seismic resilience and system life cycle sustainability. The key findings are as follows:

- Most of the studies in the existing literature have been focused on individual buildings with only a few papers considering inventory level assessments. Part of the challenge with the latter is the computational and time effort that is needed to assess the performance of an inventory of buildings. Future studies should focus on the use of high-performance computing to facilitate resilience and sustainability-based assessments of building portfolios. Also, for the regional scale studies, more emphasis should be placed on quantifying the impacts of real events, as most of the prior studies in this area have utilized simulated or hypothetical earthquakes.
- Compared to new design, there has been limited focus on the resilience and sustainability implications of seismic retrofit. However, the few existing studies in this area have shown that resilience- and sustainability-based assessments can inform the development of desirable seismic retrofit solutions.
- Several of the reviewed studies highlighted the effectiveness of multi-objective optimization and mutli-attribute decision-making in creating efficient designs for both new buildings and existing retrofits.
- Not many of the building-related studies considered non-structural components in the life cycle performance assessment. However, the few that did show that non-structural components can significantly contribute to a building's life cycle cost and environmental impact.
- The number of studies that focused on bridges was very limited, especially when compared to buildings.
- Since the current study only focused on seismic hazards, the effect of climate change was not emphasized in most of the reviewed papers. However, for other type of hazards, such as high wind, flooding and snow, the frequency of occurrence and intensity are known to be affected by changes in the climate. Studies at the intersection of resilience and sustainability for these hazards will need to consider these changes in loading intensity and occurrence frequency over the life of the structure.
- In the studies on inventory-based assessment of buildings, no distinction was made between publicly and privately owned portfolios (e.g., residential buildings versus hospitals). Future studies should consider the implications of these two types of ownership structures on the life cycle resilience and sustainability-based performance.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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