CHEMICAL ENGINEERING TRANSACTIONS
VOL. 107, 2023
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Bohong Wang, Petro Kapustenko

ISBN 979-12-81206-07-6; **ISSN** 2283-9216
DOI: 10.3303/CET23107001

A Holistic Framework to Prioritizing Building Interventions for Sustainable and Resilient Construction in Seismic-Prone Regions

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During earthquakes, damage and collapse of structures pose physical risks but also social, economic, and environmental challenges. Even buildings that appear not significantly damaged may require demolition and reconstruction to ensure their resilience. The demolition of existing buildings not only results in the loss of property and lives but also contributes to the unsustainability of the building stock. To mitigate these challenges, development of a comprehensive framework is imperative, one that can seamlessly integrate vulnerability and sustainability parameters. This holistic approach aims to achieve a sustainable building stock that not only mitigates physical vulnerabilities but also can be used to address the social and economic aspects. This study presents an interpretable, adaptable, and transparent Rapid Visual Screening (RVS) method combining machine learning, fuzzy logic, and neural networks to assess existing buildings and prioritize them based on intervention requirements and promote building stock sustainability. Buildings with higher scores indicate lower seismic sustainability ratings, emphasizing the need for intervention and improvement to enhance their resilience. The implementation of this framework facilitates the development of a safe, resilient, and environmentally sustainable building stock. In its initial stages, the proposed RVS method achieved an accuracy rate surpassing both conventional methods and the baseline. Ultimately, its application extends beyond existing buildings, as the method can also be used during the design of new buildings in seismic-prone regions.

1. Introduction

Some of the existing buildings in Europe were constructed without considering seismic design standards or based on low and moderate seismic standards (Valentina et al., 2018). After 50 to 60 y of service life, existing buildings start to show inadequacy in terms of seismic vulnerability and energy efficiency (Menna et al., 2022). Since each building has its own limited lifetime, some of the existing buildings have reached their service life. Recent earthquakes (e.g., 25 April 2015, Nepal earthquake, 6 February 2023 Türkiye-Syria earthquake) have shown the vulnerability of existing building stock. In certain European regions, seismicity poses a significant hazard, while others, like Hungary, experience moderate seismic activity. Not proper attention was given to the building vulnerability-based structural sustainability evaluation. This region needs to pay more attention to the safety of buildings because of unpreparedness. Assessing the existing buildings and taking necessary precautions can help to reduce possible life and economic losses. It is required to assess the existing building stock before an impending earthquake to take necessary measures. Existing buildings need to be assessed with practical tools to facilitate decision-making and achieve the required seismic performance.
Because the construction industry generates 36 % of European Union (EU) greenhouse gas emissions and consumes 40 % of the EU's energy (Sarhang et al., 2023), energy performance enhancement of buildings is taking special attention in the EU. Energy retrofitting is one of the most considered aspects of the existing buildings in Europe. Instead of performing energy retrofitting in addition to the strengthening of buildings against earthquakes, only performing energy investments causes a waste of resources (Keskin et al., 2020). It is not feasible to perform energy retrofitting to the buildings that may have extensive damage during an impending earthquake, as shown in Figure 1; thus, the seismic performance of such buildings needs to be improved first. Sometimes, it is preferable to demolish those buildings and construct new ones, which are designed based on

Paper Received: 28 May 2023; Revised: 29 August 2023; Accepted: 18 October 2023
Please cite this article as: Bektaş N., 2023, A Holistic Framework to Prioritizing Building Interventions for Sustainable and Resilient Construction in Seismic-Prone Regions, Chemical Engineering Transactions, 107, 1-6 DOI:10.3303/CET23107001

standards in terms of both seismicity and energy efficiency. Since the sustainability of the built environment is directly related to its resilience, without considering the resilience of existing building stock, it is not feasible to reach a sustainable built environment (Sarhang et al., 2023). The sustainable building environment not only fulfills the three dimensions of sustainability but also the non-vulnerability of the built environment (such as safety against an impending earthquake).

Figure 1: Sample damaged buildings during the 6 February 2023 Türkiye-Syria earthquake (Sorce: Earthquake Engineering Field Investigation Team (EEFIT))

Practical tools-based building assessment can pave the sustainable building stock assessment. To assess buildings, several methods can be employed, including Detailed Vulnerability Assessment (DVA), Preliminary Vulnerability Assessment (PVA), and Rapid Visual Screening (RVS). DVA methods, such as pushover analysis, time history analysis, and response spectrum analysis, are utilized to evaluate buildings by taking into account their detailed geometrical and material properties. DVA methods rely on the applied elements method and finite element method. It is important to note that conducting a DVA-based building vulnerability assessment for even a single building can be a time-consuming process, often taking days to weeks. Although DVA methods provide highly accurate results in terms of structural vulnerability assessment, applying them to assess a large building stock is not computationally feasible. On the other hand, PVA methods employ simpler engineering calculations to assess buildings. To carry out PVA methods, data and drawings of the buildings need to be collected as in DVA methods. In case the drawings are unavailable, they must be prepared accordingly. PVA methods involve taking dimensional measurements of the structural load-carrying system, followed by analysis of corresponding loads and the structural system to assess the building. Despite being more computationally efficient compared to DVA methods, PVA methods are not suitable for assessing a large building stock. RVS methods refer to techniques that require minimal time for assessing buildings. These methods are employed both before and after an earthquake to evaluate buildings. Post-earthquake assessment methods, such as GNDT (1993) and EMS-98 Scale (Grünthal, 1998), are utilized to gather building data and determine vulnerability levels and habitability or provide recommendations for further interventions, such as AeDES (Baggio et al., 2007), and ATC-20 (Applied Technology Council, 2005). On the other hand, pre-earthquake RVS methods are employed to swiftly assess existing buildings and ascertain their vulnerability prior to an impending earthquake, allowing necessary precautions to be taken. Numerous RVS methods have been developed at the national or regional levels, as noted in the review by Bektaş and Kegyes-Brassai (2022). In terms of time, these methods are the most computationally efficient for assessing large building stock.

Harirchian and Lahmer (2020) indicate that existing RVS methods do not sufficiently and accurately determine the vulnerability of existing buildings before an impending earthquake, with an accuracy rate of less than 30 %. Bektaş et al. (2022) have also highlighted similar limitations in FEMA 154. However, modifying or improving these existing RVS methods proves challenging as they are typically based on expert opinions (e.g., NRC (1993)) or rely on non-publicly available data for their development (e.g., FEMA P-154 (FEMA, 2015)). Therefore, researchers have turned to soft computing algorithms, such as fuzzy logic, machine learning, neural networks, evolutionary algorithms, and probabilistic approaches, to develop pre-earthquake RVS methods. These soft-computing algorithms-based RVS methods rely on data collected through post-earthquake building screenings, data generated by using DVA methods, and/or expert opinions. Notably, expert opinions play a crucial role in fuzzy logic-based RVS methods by establishing hierarchical relationships between parameters, defining membership functions, and establishing relational rules between input parameters and output parameters. The authors of this study have developed RVS methods based on machine learning algorithms (Bektaş and Kegyes-Brassai, 2023), which exhibit significantly higher accuracy rates (around 89 %) compared to conventional RVS methods.

The primary objective of seismic design is to create buildings that can withstand an impending earthquake. However, sustainability in earthquake engineering is often overlooked in favor of saving time and money.

Sustainable seismic design involves the use of recyclable materials, leading to reduced waste and pollution. Therefore, earthquake engineering needs to be integrated with sustainability principles to ensure that the seismic design of buildings minimizes damage to the environment, as well as social and economic impacts. By conducting strengthening and recovery interventions, the financial burden of a severe earthquake can be reduced, and the sustainability of the existing building stock can be preserved before an imminent earthquake. To achieve a sustainable transformation of existing buildings, an accurate RVS method is required to determine their vulnerability. In this study, a new framework is proposed, which combines AI algorithms (e.g., machine learning, neural networks, and fuzzy logic) for the development of an interpretable, adaptable, and transparent RVS method that accurately determines the vulnerability level of buildings, facilitating a sustainable transformation of the existing building stock. The RVS method outperforms baseline and conventional RVS methods in terms of accuracy, underscoring its potential.

2. Incorporating RVS into sustainability

Earthquakes have the potential to cause significant damage. Furthermore, the cascading effects of earthquakes can impact both people and businesses. One key aspect in preventing the wastage of energy and the subsequent increase in carbon emissions is the inclusion of structural vulnerability in the evaluation of building sustainability. Determination of the end of life or vulnerability for buildings is an important aspect of preventing possible consequences that may take place during an impending earthquake. To perform seismic assessment methods for determining building vulnerability, building information data (e.g., drawings, material and soil properties, deterioration) needed to be collected depending on the depth of the structural vulnerability assessment method. RVS methods, which are the first stage building vulnerability assessment methods, can be used to determine the vulnerability of building stock that may happen in an impending earthquake in a computationally feasible time interval. Thereby contributing to the enhancement of urban sustainability by using RVS methods (Harirchian et al., 2020).

When designing buildings, it is important to consider the whole life cycle assessment of buildings. However, many changes may be made in existing buildings, and the functionality of buildings may be changed during the lifetime. For the sustainability of existing building stock, it is difficult to predict the whole life cycle of buildings. Therefore, the sustainability of existing buildings should be considered differently. Figure 2 mainly shows the incorporation of RVS methods as seismic vulnerability assessment tools with sustainability considerations for existing buildings. Based on the determined structural vulnerability using RVS methods, the buildings can be classified as Safe, Uncertain, or Unsafe. The buildings that are classified as Uncertain are needed to be further assessed by performing further detailed assessment methods, as shown in Figure 2.

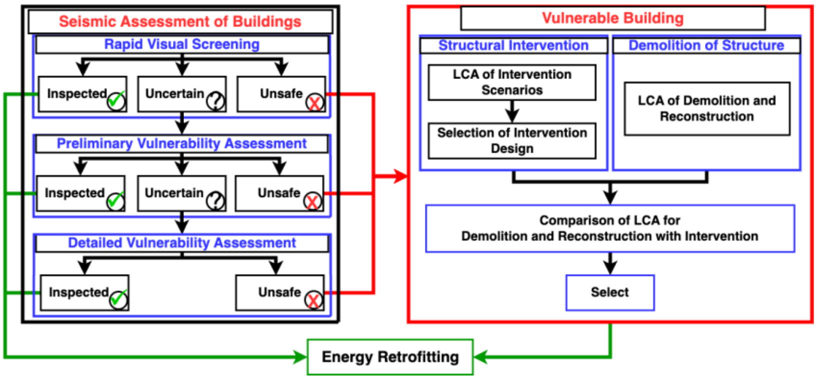

Figure 2: Structural vulnerability-based sustainability considerations to select intervention types (Compiled based on Keskin et al. (2020))

The buildings that are classified as vulnerable need to go through extensive life cycle analysis to determine demolish, repair, and/or strengthening techniques. There are many retrofitting techniques (e.g., jacketing, wall thickening, adding shear walls), which are alternatives to each other, that can be used to strengthen buildings. By performing retrofitting techniques, the weaknesses in the building can be eliminated to enhance structural performance. The combination of a flowchart for determining structural vulnerability, integrated with sustainability considerations and energy retrofitting, has been illustrated in Figure 2. If a building is not repairable or the repairs are not feasible, it is necessary to demolish the vulnerable building. However, if vulnerable buildings can be strengthened to become more sustainable, they can be reinforced to reduce the environmental burden of demolition and subsequent reconstruction. Life Cycle Cost Analysis (LCA) is a decision-making process for sustainability-related decision-making. The buildings that are decided to be strengthened need to be examined by performing LCA in addition to the structural analysis to decide the most suitable retrofitting technique. After performing the process shown in Figure 2, the energy retrofitting of buildings can finally be implemented, thereby enhancing the sustainability of energy retrofitting intervention.

3. A real case study effect of enhancing building performance

Since the performance of buildings depends on the parameters that are considered in RVS methods to assess a building, the intervention type (e.g., retrofitting or strengthening) also depends on those parameters. Such as plan irregularity, vertical irregularity, and soft story formations, should have been intervened to prevent or alleviate possible harmful consequences. Based on the building characteristics, local or global interventions can be performed to enhance building performance.
The buildings that have been intervened by performing retrofitting or strengthening should have shown better performance than their earlier performance level. For example, in the case of residential buildings, the intervened building is expected to show the life safety performance level during an impending design earthquake. In this manner, the recent 6 February Türkiye-Syria earthquake has shown the importance of strengthening, as shown in Figure 3. These buildings have been constructed in 1974. In 2008, strengthening interventions were performed on those buildings based on the 2007 seismic design code of Türkiye (Ministry of Public Works and Settlement, 2007). One of the three structures, as shown in Figure 3(c), has been strengthened by adding external shear walls adjacent to the existing shear walls. The other standing building has been strengthened by adding infill walls to the entrance floor and performing CFRP retrofitting technique to the infill walls and columns, as shown in Figure 3 (a-bottom, b). The observed damage in the building strengthened using the CFRP method has significantly exceeded the damage mitigated in the building strengthened by the addition of shear walls. Despite being classified as High vulnerability after the severe earthquake sequence, these buildings successfully met the requirements for the life safety performance level.

(a) *(b)* *(c)*

Figure 3: (a-top) post-earthquake performance comparison of three reinforced concrete buildings, (a-bottom and b) building strengthened using CFRP technique (Tan, 2009), (c) building strengthened by adding shear walls. (Source: EEFIT)

However, the third building, which had not undergone any strengthening intervention techniques to enhance its seismic performance, collapsed during the earthquake sequence. The debris field from the collapsed building can be seen in the approximate top middle part of Figure 3 (a-top). Figure 3 highlights how structural retrofitting interventions extend the structural service life of existing buildings (Belleri and Marini, 2016). The strengthening of buildings not only enhances the performance of buildings but also prevents loss of life. Finally, these intervention techniques can be decided based on the expected lifetime of the structure and life safety cost analysis to reduce the building footprint (environmental impact). Given these considerations, ensuring the safety and resilience of buildings becomes essential. As a result, a thorough evaluation of the building stock using efficient RVS methods becomes critical, laying the groundwork for the implementation of cautious precautions.

4. Proposed method for sustainable assessment of existing buildings

Efforts to implement sustainability in the built environment have been concentrated upon, mainly revolving around the triple bottom line: environmental, financial, and social aspects. Environmental sustainability aims to minimize the building's footprint and detrimental impact on the natural environment, encompassing energy efficiency, renewable energy, water conservation, sustainable materials, and waste reduction. Financial sustainability focuses on the long-term economic viability of buildings, and for existing structures, optimized financial performance can be achieved through tools like LCA, energy cost savings, and prudent management of occupancy and maintenance expenses. Meanwhile, social sustainability prioritizes the well-being and quality of life for building occupants, encompassing aspects such as indoor air quality, accessibility, community engagement, and adaptive reuse. By taking into account these three pillars of sustainability, buildings can be effectively promoted towards a more sustainable future. The principles of sustainability outlined can be applied to existing buildings by using RVS methods, as depicted in Figure 2.

While soft computing algorithms (e.g., machine learning, neural networks, fuzzy logic) based developed methods have demonstrated high accuracy rates compared to the conventional methods (less than 30 %), they still have certain constraints. For instance, fuzzy logic-based RVS methods can be complex to develop, requiring expert knowledge to define membership functions and rules. This approach can be subjective, leading to bias and inconsistency. On the other hand, machine learning and neural networks-based RVS methods depend heavily on data and corresponding parameters, which can lead to overfitting or underfitting. Neural networks require large amounts of data to reveal relationships between parameters and decision-making processes. These algorithms can be difficult to interpret and may not be suitable for obtaining transparent and interpretable results. To overcome these limitations, an interpretable, transparent, and adaptable RVS method development framework has been proposed for assessing existing buildings to mitigate the devastating consequences of earthquakes. The method can be developed using fuzzy logic within a hierarchical framework. This method encompasses the formulation of the following fundamental elements: (I) construction of a hierarchical structure to illustrate parameter interrelationships and assess the level of damage, (II) determination of membership functions for each parameter, and (III) establishment of the required fuzzy rules.

The hierarchical structure plays a crucial role in diminishing the overall count of required rules for model creation while upholding the interpretability of rules and the developed method. In the hierarchy creation phase, machine learning algorithms (e.g., fastcluster, scipy) or Analytical Hierarchy Processes (AHP) are recommended for creating a hierarchy that can be employed for the reduction of computation costs in fuzzy logic-based RVS framework. This study utilizes pdist and linkage functions from scipy for hierarchy creation. During the membership function determination phase, the ANFIS algorithm, a coupling algorithm of fuzzy logic and neural networks, can be employed to establish initial membership functions from data for accurately depicting the relationship between input parameters and the target feature. In the establishment of the rules phase, fuzzy logic rules can be extracted from data using machine learning algorithms (e.g., decision trees) or evolutionary algorithms (e.g., genetic algorithms) to represent the relationships between input parameters and the target variable. This study utilizes the decision tree algorithm for rule generation. In the development of the proposed framework, post-earthquake screening data from the 2015 Gorkha, Nepal earthquake are being used, similar to the methods previously established by the author through machine learning and neural networks. The initial creation of the framework has been successfully devised and has shown a 44 % rate of accuracy. Although the model of the in-development framework did not achieve a high accuracy rate like that of previously developed methods, it still managed to surpass both the baseline accuracy level of 33 % (3 classes classification; Low, Moderate, High) and the accuracy rate of conventional methods (less than 30 %) mentioned in the literature.

Using the proposed RVS method, existing buildings can be assessed, classified, and ordered according to the severity of their structural vulnerabilities, as illustrated in the Rapid Visual Screening portion of Figure 2. This classification can serve as a basis for making sustainable decisions in further steps. The determined structural vulnerability classes by implementing the RVS method can be used to proceed with further steps required to achieve sustainable decisions, as has been done in existing buildings explained in the previous section.

5. Conclusions

This paper highlights the importance of incorporating RVS methods for the vulnerability assessment of existing buildings against earthquakes with sustainability principles. To demonstrate the effectiveness of strengthening interventions on building performance, a real case study example of retrofitted buildings and their corresponding performance during the 6 February 2023 Türkiye-Syria earthquake has been presented. The real-world building performance during the earthquake highlights the importance of structural vulnerability assessment and correspondingly strengthening interventions in terms of sustainability. Based on this premise, a new interpretable, adaptable, and transparent RVS method, under development, using a combination of soft computing algorithms (e.g., machine learning, fuzzy logic, and neural networks), is proposed to be developed for determining the structural vulnerability of buildings. The proposed RVS method can be used to support decision-making processes in assessing building vulnerability, reducing possible life and economic losses, and mitigating environmental impact to improve community resilience to earthquakes. The proposed RVS method's early stage surpasses conventional methods and the baseline. Additionally, the presented RVS method can be easily integrated with sustainability parameters, with significant implications for urban sustainability in earthquake-prone regions. Finally, additional research endeavors are presently underway, aimed at enhancing and extending the method succinctly outlined within this study.

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