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FUZZY LOGIC BASED RAPID VISUAL SCREENING METHODOLOGY FOR STRUCTURAL DAMAGE STATE DETERMINATION OF URM BUILDINGS

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Abstract. Most of the Unreinforced Masonry (URM) buildings are quite old in Europe based on "*Building stock inventory to assess seismic vulnerability across Europe*" [1] report. Following the earthquakes (Albania, Italy, etc.) that occurred in Europe, it was revealed that masonry buildings are extremely vulnerable. While probabilistic and deterministic approaches are important for examining a small number of buildings, they do not offer the opportunity to examine a large building stock in a short period of time. Rapid Visual Screening (RVS) methods are used to identify building pre- and post-earthquake vulnerability. Several RVS techniques have been presented in literature over last 30 years. Recent earthquakes have highlighted critical necessity of a rapid vulnerability assessment method for pre-earthquake warning, mitigation, preparedness, and post-earthquake damage state assessment of existing buildings. These findings demonstrate the importance of using an accurate RVS technique to inspect buildings. Due to the subjectivity of the screener, these RVS methods contain uncertainty and vagueness. Fuzzy Inference System (FIS) overcomes nonrandom uncertainty and vagueness by considering building characteristics in terms of their degree of truth. This paper introduces a FIS-based S-RVS case implementation and compares FIS-based Soft-RVS (S-RVS) to traditional RVS methods for identifying building damage state taking into account rapid visual assessment reports about damage caused by the 2019 Albania earthquake. To determine the damage states of URM buildings, 40 buildings damaged in the 2019 Albania earthquake were analyzed and processed to use in the applied fuzzy logic mathematical model. Initial findings demonstrate that the site-specific FIS-based S-RVS method is capable of accurately determining the damage states of at least half of the buildings.

1. INTRODUCTION

A portion of the existing building stock was constructed prior to the adoption of design standards, making these structures vulnerable to damage. Furthermore, the considered former standards are categorized as low or medium design codes because of subsequent developments in the old design standards. Therefore, existing buildings designed based on low or moderate design codes are susceptible to damage. Also, increasing population, migration from rural to urban areas, war-related migrations result in massive urbanization. Because of rapid urbanization, structures are not appropriately built or erected. This is why large building stock needs to be assessed in order to prevent loss of life and property. There are several methods that can be used; however, Rapid Visual Screening (RVS) methods offer a fast possibility for such assessments.

This type of evaluation would have a high significance so far earthquakes are one of the most disastrous events that cause loss of life and property. Therefore, seismic vulnerability assessment of existing buildings in earthquake-prone areas has critical importance in determining, to take required measures in order to prevent casualties and/or catastrophes prior to an impending destructive earthquake. The vulnerability of a building is assessed employing three-tiered methodologies, each with different degrees of assessment capabilities. These assessment methodologies are called Detailed Vulnerability Assessment (DVA), Preliminary Vulnerability Assessment (PVA), and RVS to perform vulnerability assessment of buildings from most detailed to simple, respectively.

DVA methods conduct detailed analyses of buildings and exploit software to model and analyze buildings. Since DVA methods take into account structural system nonlinearity and anticipated seismic excitation, they are fundamentally complex. DVA exploits finite element method and applied element method. Also, the implementation of these analysis types such as pushover analysis, time-history analyses, and incremental dynamic analyses, are more complicated than designing a building. Even though DVA methods are very precise and accurate they require a high amount of time for assessing a single building. Implementation steps of these methods are explained in standards such as FEMA 356 [2], Eurocode 8 [3], and FEMA P-695 [4].

In **PVA methods,** simple engineering analyses are carried out. The PVA implementation stages include collecting and/or preparing drawings, identifying structural load carrying system elements and carrying out dimensional measurements, calculating different load types and configurations, and performing strength-related checks. PVA methods are operated to examine buildings at the global and element levels. Even PVA method is comparatively less time-consuming than DVA it is not feasible to implement for assessing a large building stock. Therefore, fast and reliable RVS methods are required to screen buildings.

RVS methods are employed to examine buildings before or after an earthquake. RVS methods are performed by a street walk survey and/or by excessing into the buildings if it is safe to enter. The outcome of the RVS methods is a classification that shows whether the building is safe or uncertain for pre-earthquake screening. When the building is classified as safe means the building is going to show expected design occupancy class performance requirements (life safety, initial occupancy, etc.) during an impending earthquake. If the building is identified as uncertain, the considered building is required to be assessed by employing further detailed assessment methods (PVA and/or DVA methods).

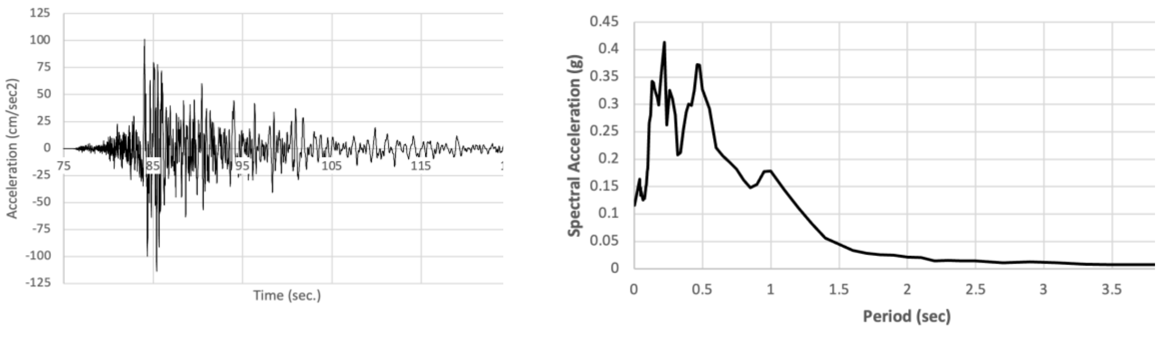
The main advantage of RVS methods is having the capability to examine large building stock compared to more detailed methods in a short time interval. There are many RVS methods that have been developed in the last 3 decades. The first RVS method is developed in Japan for RC buildings by JBDPA [5] in 1977. However, for the broad type of the buildings, the first RVS method was developed in 1988 as FEMA 154 [6] and 155 [7] in the US. Following the development of the FEMA RVS method, many RVS methods have been developed or updated all around the world such as in the US [8], Greece [9], Canada [10], Turkey [11], EMS-98 [12], Italy [13], etc. Besides, conventional RVS methods are frequently employed for research and development purposes [14–17], and assessment of existing structures [18–20]. RVS methods parameters are irregularities (such as plan and vertical), construction year, construction quality, building type, etc. Furthermore, **Soft-RVS** (S-RVS) techniques using computer algorithms are recommended to enhance conventional RVS methods [21,22]. S-RVS methods are based on Machine Learning (ML), Fuzzy Logic (FL), Neural Networks (NNs), probabilistic, integrated methods, etc. as stated by Harirchian et al. [23].

It is crucial to assess existing buildings to quantify their safety levels and overcome potential economic and life losses by employing RVS methods. In addition to the complexity of the conventional RVS decision-making framework, the arising vagueness and uncertainty in the assessment are required to be overcome [21]. Since it is essential to have a simple and accurate method that can overcome uncertainty and vagueness arising from the subjective assessment of existing buildings, this study presents an S-RVS method by integrating Fuzzy Inference System (FIS) with RVS parameters to overcome such uncertainties and complexities in determining safety levels of URM buildings. The proposed methodology allows rapid assessment of building stock. The results revealed that the FIS-based S-RVS method outperformed conventional RVS methods in evaluating building damage states. Furthermore, engineers, architects, and experienced screeners can apply the proposed S-RVS method to mitigate the destructive effects of impending earthquakes on existing buildings.

This paper addresses site seismicity and building types in section 2, the FIS technique in section 3, and the development of the FIS-based S-RVS framework for 40 URM buildings in section 4. Section 5 illustrates the findings of this study and discusses them, while section 6 provides the conclusions.

2. SITE SEISMICITY AND BUILDING TYPE

In order to develop the S-RVS method for the assessment of existing buildings, site seismicity and attributes of building parameters are required to be collected. For this study, post-earthquake building screening data from the date following the Tirana earthquake was obtained, hence the area of investigation is Tirana. An earthquake with 22 km hypocentral depth and 6.4 moment magnitude scale occurred in the Northwestern region (Durrës) of Albania in 2019 [24], which caused extensive damage to the buildings in nearby residential locations. The recorded seismic activity East-West direction in the Tirana station is shown in Figure 1–a. The corresponding determined acceleration response spectrum is illustrated in Figure 1–b.



(a) (b)

Figure 1: (a) Acceleration time-history data and corresponding (b) site specific acceleration response spectrum of 2019 Albania earthquake

The post-earthquake building screening data of 40 Unreinforced Masonry (URM) buildings were collected from Tirana after the 2019 Albania earthquake. The characteristic URM buildings from Tirana Albania are illustrated in Figure 2. The URM buildings under consideration in this study have reinforced concrete slabs in story levels. Furthermore, as illustrated in Figure 2-a, corner columns were constructed in some buildings based on the intuition of mason without structural design considerations. The building screening data was collected by the Hungarian team, dispatched by the Hungarian government to Albania.

(a) (b)

Figure 2: Sample of the considered URM buildings in Tirana, Albania

3. FIS METHODOLOGY

In the case of this article, fuzzy logic code has been developed to provide an enhanced S-RVS method. Fuzzy logic was introduced in 1965 by Zadeh [25]. According to the rules and membership functions, the Fuzzy Inference System (FIS) interprets the values in the input vectors (crisp input) and produces the output vector (crisp output) values. The schematic representation of the FIS is illustrated in Figure 3.

The process of transforming crisp sets into fuzzy sets using membership functions is known as fuzzification. It is depicted in Figure 3 as the fuzzifier. Assessment or opinions of a decision-maker in a given case with uncertainties is termed as rules. Inference, which is FIS reasoning process, is the stage where input fuzzy sets are mapped to output fuzzy sets. The process of transforming fuzzy sets into crisp sets is called defuzzification, which is the inverse of fuzzification and depicted as the defuzzifier in Figure 3.

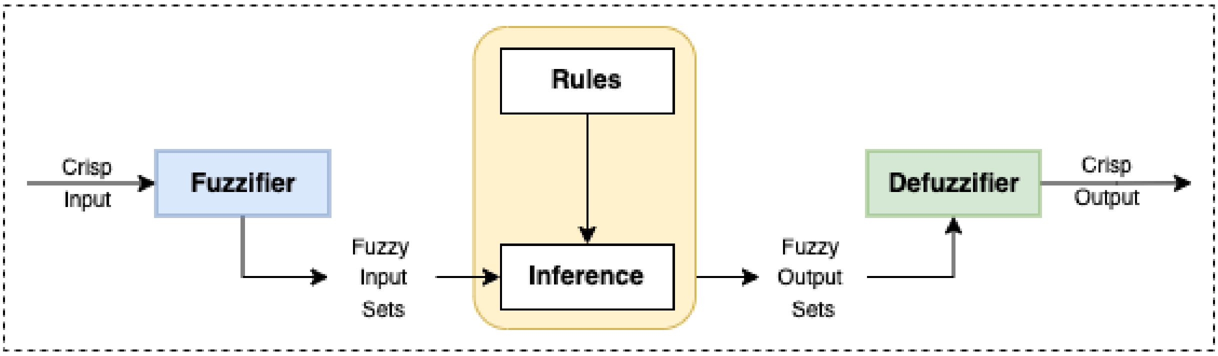


Figure 3: Fuzzy inference system framework

The literature discusses several types of membership functions such as triangular, trapezoidal, gaussian, and sigmoid. The form of these membership functions is determined based on the characteristics of the parameters under consideration. Trapezoidal and triangular membership functions were employed in this study, as shown in Figure 4.

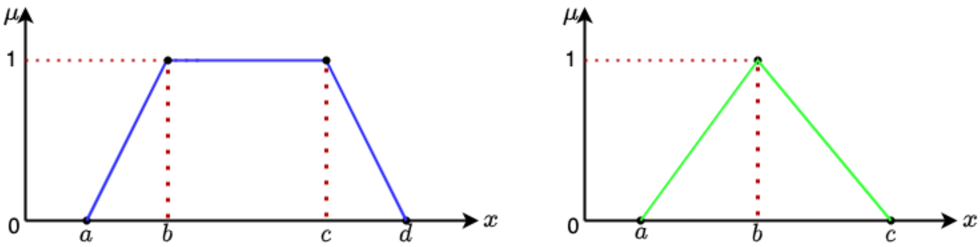


Figure 4: Schematic representation of the trapezoidal and triangular membership functions

Rules formulation is required for the establishment of FIS as illustrated in Figure 3. The Mamdani [26] type rule formation based on the *"if-then"* statement and fuzzy logic operator *"and"* is shown in Equation (1)

$$Rule_i: if\ x_1\ is\ A_{i_1}\ and\ x_2\ is\ A_{i_2}\ then\ y\ is\ B_i, \qquad i = 1, 2, \dots, n \qquad (1)$$

Where, input linguistic parameters (antecedents) are illustrated as x_1 and x_2. Input sets are illustrated as A_{i_1} and A_{i_2}. y is the output linguistic parameter (consequent). B_i is the output set. The required number of rules is illustrated as n. There are mainly three different advantages of using fuzzy logic as stated by Dritsos and Moseley [27]. (I) It allows experimenting and demonstrating how the parameters can be used in RVS applications and may be better categorized using linguistic parameters. (II) It considers the degree of parameter rather than categorical variables (yes, no, etc.). (III) The ability to use neural networks to train fuzzy logic. The advantages I and II of employing fuzzy logic listed above were applied in this investigation under the title FIS Based S-RVS.

4. FIS BASED S-RVS DEVELOPMENT FOR MASONRY BUILDINGS

The research presented in this paper focuses on developing a FIS based S-RVS method for masonry buildings to overcome uncertainties built up in conventional RVS techniques. This is even more important, so far a large part of the European building stock consists of URM buildings. This building stock was constructed without considering seismic design codes, or designed and constructed based on low, or moderate design codes [1]. Therefore, it is essential to examine these buildings before an impending earthquake by employing a more accurate RVS method.

The use of RVS methodologies and the capacity of masonry buildings are openly subjected to uncertainty. The major issue with conventional RVS methods is the unclear interaction of the parameters, not the parameters themselves. Another issue is that it might be difficult for screeners to simply respond yes or no in scenarios that are difficult to identify. Fuzzy logic based RVS can be adopted to account for such uncertainties in such scenarios enabling the screener to easily categorize the current condition as low, moderate, or high.

FIS is a powerful system since it models complicated situations while tackling uncertainty and vagueness within the framework depicted in Figure 3. It is assumed in this study that fuzzy logic has the capability of enhancing RVS methods by processing linguistic variables and considering uncertainty. So, the goal of the developed method is to prove the applicability of FIS based S-RVS approach. Parameters used for this evaluation are shown in green boxes in Figure 5. The outcome parameter is indicated in the red box, while some of the intermediate parameters are shown in yellow boxes.

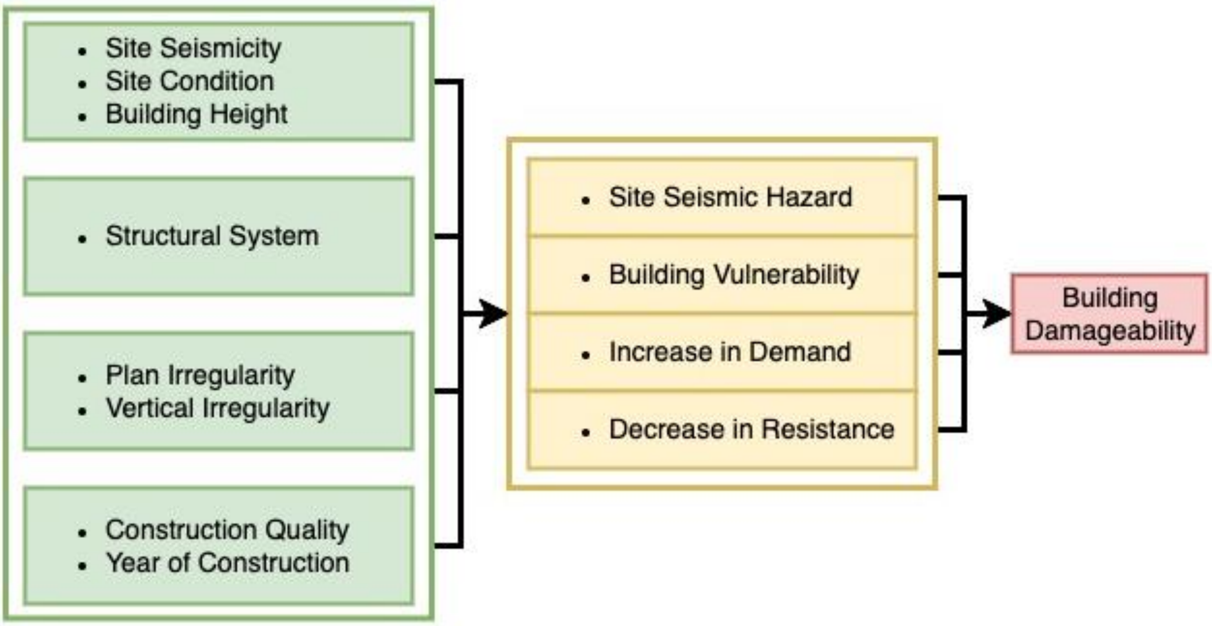


Figure 5: Parameters of the developed FIS based S-RVS method

Input parameters, which shown in green boxes in Figure 5, taken into account in this research are:

- The seismic zone designated to the site, as well as the corresponding design response spectrum or site-specific response spectra, are considered to identify **site seismicity**.
- **Site conditions** represent local soil type (such as A, B, C), distance to the epicenter of an earthquake, sloping site, etc.
- **Building Height** is evaluated based on number of stories and average building story

height. The average building story height is defined as 2.8 m for URM buildings based on [28–30].

- Buildings with various **structural systems** behave in different ways. Furthermore, even though they have the same structural system, URM buildings respond differently to seismic excitation depending on whether they are standalone, at the row end, or in the row middle.
- Buildings with at least one of the reentrant corners, torsional irregularity, diaphragm discontinuity, nonparallel systems or out-of-plane offsets are classified as having **plan irregularities**. The buildings with plan irregularity have L, T, U, +, etc. irregular shapes in the plan.
- Buildings with at least one of the soft-story (stiffness irregularity), weak story (discontinuity in structural capacity), vertical geometric irregularity, mass irregularity, or in-plane offset (discontinuity) of load-carrying elements are classified as having **vertical irregularity**.
- The degradation of the structural material, components that make up structural system of a building, and cracks in the wall reveal **construction quality** of the building.
- The **year of construction** for a building is important to determine whether the design codes are incorporated or not for the design of the building, as well as whether the considered design code is low, moderate, or high.

Membership functions represent a graded association of fuzziness and characterize all of the fuzziness in a fuzzy set. Membership functions of each variable can be determined based on open left and right (trapezoidal and triangular), triangular, and trapezoidal fuzzy sets in order to implement the FIS based S-RVS method. A sample membership function, which contains open left (very low), open right (very high), and triangular (low, moderate, high) membership function shapes, operated to define the building vulnerability parameter is illustrated in Figure 6.

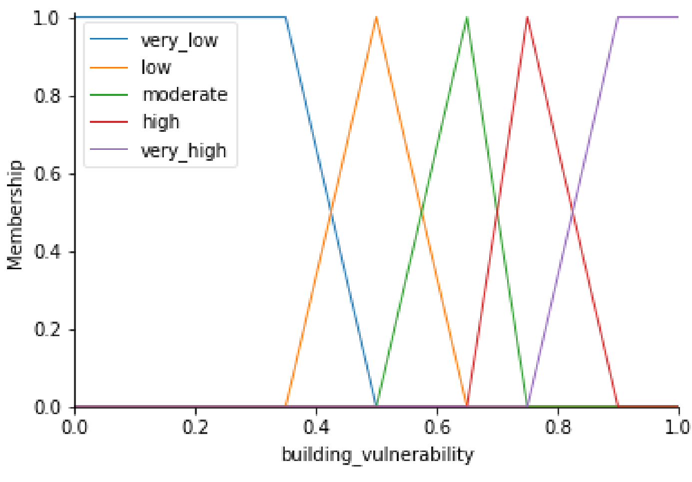


Figure 6: Building vulnerability membership function

The link between the input parameters and the output parameters of a system, which are linguistic variables, is established via fuzzy rules consisting of conditional expressions. A sample rule formation is described as follows in the developed FIS based S-RVS method to determine the increase in demand by considering plan irregularity and vertical irregularity.

1. If the vertical irregularity is **low** and plan irregularity is **low**, then the increase in demand is **low**.
2. If the vertical irregularity is **low** and plan irregularity is **moderate**, then the increase in demand is **low**.
3. If the vertical irregularity is **low** and plan irregularity is **high**, then the increase in demand is **moderate**.
4. If the vertical irregularity is **moderate** and plan irregularity is **low**, then the increase in demand is **low**.
5. If the vertical irregularity is **moderate** and plan irregularity is **moderate**, then the increase in demand is **moderate**.
6. If the vertical irregularity is **moderate** and plan irregularity is **high**, then the increase in demand is **high**.
7. If the vertical irregularity is **high** and plan irregularity is **low**, then the increase in demand is **moderate**.
8. If the vertical irregularity is **high** and plan irregularity is **moderate**, then the increase in demand is **high**.
9. If the vertical irregularity is **high** and plan irregularity is **high**, then the increase in demand is **high**.

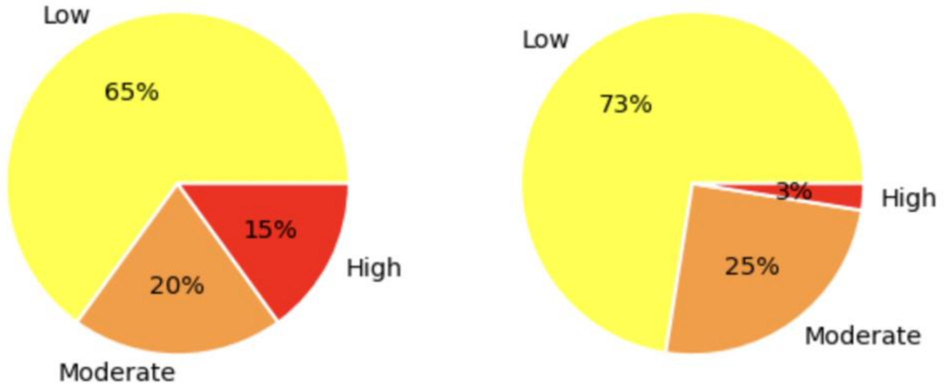
The aforementioned information has been integrated into the FIS framework as illustrated in Figure 3 for the development of a FIS-based S-RVS method. Then, the post-earthquake screening data of 40 URM buildings in Tirana, Albania, was utilized to test the integration of rules and membership functions. Finally, the safety levels of these buildings are classified using the developed S-RVS method, and the results are compared and further discussed under the heading Results and Discussion.

5. Results and Discussion

Traditional RVS methods employed frequently for seismic safety evaluations of existing buildings, while well developed and validated, may be insufficient to determine building damage states accurately. Therefore, there is a little room for further development of RVS methods. Aside from the fact that RVS procedures are unlikely to be highly accurate, each improvement directly contributes to the safety of lives and property. Therefore, the research presented in this paper focuses on developing an S-RVS method for masonry buildings to overcome uncertainties built up in conventional RVS techniques.

The FIS framework depicted in Figure 3 in this study was exploited to develop the FIS-based S-RVS method. This framework was operated using post-earthquake screening data of 40 URM buildings obtained following the 2019 Albanian earthquake. The post-earthquake building screening data classified 65 percent of buildings as Low, 20 percent as Moderate, and 15 percent as High as illustrated in Figure 7–a. Aside from the post-earthquake screening data of the input parameters, the parameters required for the establishment of the FIS framework such as membership functions and rules are defined as described under the heading FIS Based S-RVS Development for Masonry Buildings. Eventually, under the FIS framework, an S-RVS method is presented in this paper.

The buildings considered are classified as having three damage states: Low, Moderate, and High, by employing the developed S-RVS method and exploiting the input data. The percentages of buildings damage states acquired as a result of this classification are illustrated in Figure 7–b. The building assessment performed using the FIS-based S-RVS technique categorized approximately 73 percent of the buildings as Low, 25 percent as Moderate, and about 3 percent as High. Make further comments about the results.



(a) **(b)**

Figure 7: Post-earthquake buildings damage states and determined FIS based building damage states

To demonstrate the accuracy of the proposed FIS-based S-RVS method, the damage states classification accuracy of the proposed method is required to be demonstrated in comparison with post-earthquake screening data. **Comparing** the S-RVS-based damage states one to one with the post-earthquake screening damage states is an approach used to verify the accuracy of the results obtained. One-to-one comparison of each post-earthquake and the FIS based S-RVS damage states for each building demonstrates 57.5 percent accuracy.

Since this study presented the development of the FIS based S-RVS method as an alternative enhanced RVS method to conventional RVS methods, the findings are required to be compared to those of conventional RVS methods. In this context, the forthcoming research conducted by the author's research group [31] demonstrated that conventional RVS (FEMA P-154 [8]) based screening obtains only 25 percent accuracy. As a consequence, the findings of this study prove that the S-RVS results concerning masonry buildings outperform the results of conventional RVS, and it aligns with the results of S-RVS methods developed for RC buildings by Harirchian et al. [32]. As a result, the FIS based developed S-RVS method exhibited the capacity to reliably determine the damage states of URM buildings.

The findings illustrate that the proposed S-RVS method outperformed the conventional RVS method in terms of accuracy. Therefore, the suggested FIS-based S-RVS method may be exploited to assess the building safety levels before an impending earthquake. In contrast to conventional RVS methods, beyond categorization with linguistic parameters such as yes or no, the accuracy of the system may be boosted by systematically altering the number of linguistic classifications and intervals using fuzzy sets.

6. CONCLUSION

Existing buildings are required to be assessed using RVS methods to mitigate their vulnerability to earthquake-induced damage. The damage to 40 URM buildings caused by the earthquake in Tirana, Albania in 2019 is taken into consideration for this study. The corresponding buildings damage states were exploited in this study to demonstrate that the proposed FIS-based S-RVS method is effective. FIS has the capability to process linguistic variables, therefore, using linguistic input parameters, the post-earthquake damage states of the buildings were classified into three linguistic categories: low, moderate, and high. The FIS-based developed S-RVS approach was to assess the damage states of these structures in light of post-earthquake assessment data. The findings of the author's research group and studies in the literature were exploited to demonstrate that the S-RVS method outperforms conventional RVS methods. When the categorized building safety levels were compared to the post-earthquake screening data, the proposed S-RVS method outperforms conventional RVS methods with an accuracy rate of 57.5 percent in determining the safety levels of the considered URM buildings. However, a comparison of the FIS-based S-RVS method to conventional RVS methods can be conducted in future investigations. The achievements that the proposed S-RVS method has made in comparison to conventional RVS methods can be demonstrated by comparing FIS-based S-RVS building damage classification simultaneously with post- and pre-earthquake screening data.

Consequently, this study demonstrated that the FIS-based S-RVS method can be applied to enhance conventional RVS methods for determining building damage states. Besides, soft computing algorithms like machine learning and neural networks may be employed to enhance traditional RVS methods. Therefore, the author is currently conducting research that employs these computer algorithms to consider vagueness and uncertainty for enhancing conventional RVS methods.

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