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First level seismic risk assessment of old unreinforced masonry (URM) using fuzzy synthetic evaluation

Ram Krishna Mazumder [a,b,*], Sohel Rana [a], Abdullahi M. Salman [c]

[a] Institute of Earthquake Engineering Research, Chittagong University of Engineering and Technology, Chittagong, 4349, Bangladesh
[b] Department of Civil, Environmental and Architectural Engineering, University of Kansas, Lawrence, KS 66045, USA
[c] Department of Civil and Environmental Engineering, The University of Alabama in Huntsville, Huntsville, AL, 35899, USA

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ABSTRACT

The seismic risk of old unreinforced masonry (URM) buildings is inherently high due to their non-ductile behavior. Masonry buildings constructed without seismic resistance characteristics have performed poorly in previous earthquakes. There is a clear need for reliable vulnerability assessment techniques for identifying the most vulnerable buildings to support risk mitigation strategies in urban areas. Seismic risk evaluation and mitigation planning are often performed in a multi-level risk assessment approach, where the first level is meant to identify relatively vulnerable buildings that require further assessment. This paper proposes a fuzzy synthetic-based first level seismic risk evaluation technique for identifying relatively risky URM buildings in an urban area. Fourteen risk factors, categorized into five indexes, are used to estimate the overall seismic risk of individual URM buildings. The proposed approach is illustrated for 81 old URM buildings of an urban settlement at Shakhari Bazar, Dhaka city, Bangladesh, using data collected as part of a technical assessment project by Dhaka City Corporation. The results of the case study show that most of the buildings (more than 90%) have high to a very high level of risk and are expected to suffer severe damage in case of future large earthquakes in this region. The outcome of this study is compared with a previous study conducted for the same urban settlement. The proposed method provides a simple procedure for prioritizing riskiest URM buildings for seismic rehabilitation.

1. Introduction

A large portion of older buildings in developing countries is made of Unreinforced Masonry (URM). Due to their highly rigid and low-ductile behavior, URM buildings behave poorly under earthquake loadings [1]. Past earthquakes have caused severe structural and non-structural damage to URM buildings, which led to substantial economic and life losses [2–5]. For instance, a majority of damaged buildings (about 773,400) in the 2015 Nepal earthquake were URM structures [6]. An estimated 8,700 deaths and 16,800 injuries were reported after this earthquake [6]. The 2010 Chile earthquake damaged 208,582 structures, including old masonry buildings [7]. Similarly, at least 70,000 deaths and 80,000 injuries were reported after the 2005 Kashmir earthquake in Pakistan, where approximately 450,000 masonry buildings were damaged [2]. The 2001 Bhuj earthquake in India caused about 20,000 deaths, more than 60,000 injuries, and an estimated US$ 2.0 billion losses [8]. The brittle nature of masonry structures was mainly responsible for the severe damage to buildings and loss of lives in the Kashmir and Bhuj earthquakes [9,10]. Due to the large volume of vulnerable buildings in urban areas, seismic risk assessment of masonry buildings is crucial for prioritizing the seismic risk mitigation tasks at a city scale, particularly for developing countries.

Seismic risk analysis requires quantifying seismic hazard, seismic vulnerability, and possible consequences. Seismic hazard estimates the likelihood of potential earthquakes in a specific area by aggregating information related to ground shaking, soil conditions, and fault-rupture [11,12]. The seismic vulnerability of a building is evaluated by its weakness or inability to withstand damage from earthquakes [11]. Seismic vulnerability assessment evaluates various performance criteria (e.g., configuration, geometry, structural deficiency) of a building to identify vulnerable parameters that potentially influence the overall performance of the building against earthquake loading. Seismic consequence measures possible structural damage and casualties due to an earthquake. While developing risk mitigation strategies for urban areas, it is often not possible to perform a detailed seismic risk evaluation of each building separately due to financial, time, and resource

* Corresponding author. Institute of Earthquake Engineering Research, Chittagong University of Engineering and Technology, Chittagong, 4349, Bangladesh.
E-mail addresses: rkmazumder@cuet.ac.bd (R.K. Mazumder), ranasohel@cuet.ac.bd (S. Rana), ams0098@uah.edu (A.M. Salman).

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constraints. Therefore, seismic risk assessment in urban areas is often performed in a multi-level approach. In the first level, relatively vulnerable buildings are identified using visual inspection. Visual screening allows data collectors to perform a quick survey around the buildings to identify potential deficiencies (e.g., topological, configuration, structural conditions) and rank them based on a prescribed checklist (e.g., FEMA 154, [13]). The identified vulnerable buildings in the first level are then prioritized for subsequent in-depth structural assessments. The second and third-level risk assessments are based on rigorous structural analysis where adequacy for lateral force resisting systems, non-linear behavior, capacity against designed earthquake load, etc., are checked for each building.

Research on seismic performance evaluation of URM buildings on a large scale has received significant attention in the last decade. Several commonly used first-level risk assessment techniques are discussed in Section 2.1. First-level risk assessment is particularly useful when it is applied to a regional scale for classifying a large number of buildings within a shorter period [11,14]. Since first-level evaluation is typically based on simplification and approximate indexes, these approaches cannot provide seismic behavior of buildings with greater accuracy [15]. Therefore, more detailed second and third levels of structural analysis are followed while evaluating an individual building to better predict expected seismic behavior [11]. The behavior of URM buildings is inherently complex due to the heterogeneity between the masonry units and joints. Researchers followed various approaches for analyzing and modeling in-depth structural performance of historical URM buildings to reduce their seismic risk, such as equivalent frame method [16], finite element analysis [17], and adaptive limit analysis [14,15,18–20].

Several researchers have used second and third-level analysis for seismic risk assessment of masonry buildings. For example, Bothara et al. [3] experimentally investigated the influence of various parameters on the seismic performance of masonry buildings. Siano et al. [21] used an equivalent frame model to analyze URM walls' non-linear seismic behavior. Bracchi et al. [22] quantified the uncertainty in equivalent frame modeling of the masonry structure. Valente et al. [17] performed 3D finite element analysis to investigate masonry aggregates' non-linear behavior. Grillanda et al. [14,15] applied kinematic limit theory for analyzing the local behavior of URM aggregates. Chiumiento and Formisano [23] evaluated the performance of masonry units as individual buildings and as a group in a cluster. Although these approaches can provide great detail of the seismic capacity of URM buildings, these approaches are not suitable for regional seismic risk assessment given a large amount of information and computational time required [14]. Hence, urban planners and decision-makers are often interested in knowing the approximated behavior of buildings through rapid visual techniques (i.e. first-level risk evaluation) for regional seismic risk analysis [24]. Several approaches exist for evaluating first-level risk of various buildings archetypes. However, research focused on developing first-level risk evaluation of old URM buildings is rare.

This study aims to develop a simplified first-level seismic risk assessment technique for prioritizing URM buildings in risk mitigation plans of urban areas. Determining the first-level risk of URM buildings is complex and challenging due to the fact that it requires handling qualitative and quantitative structural parameters through engineering judgment, leading to significant uncertainty in the evaluation process. Hence, this study proposes a novel fuzzy logic-based synthetic technique for evaluating seismic risk of old URM buildings in urban areas. The technique is easy to use as the required information can be obtained through a walk-down survey. The proposed technique can be applied to prioritize the riskiest buildings that required urgent investigation in urban areas of developing countries.

The remainder of this paper is structured as follows. Section 2 presents a rigorous literature review of existing first-level assessment techniques and past applications of fuzzy logic in civil engineering. Section 3 describes the proposed fuzzy synthetic-based first-level seismic risk evaluation approach for ranking the URM buildings. Section 4 illustrates the proposed framework for 81 URM buildings of an old settlement of Dhaka city, Bangladesh. The conclusions are provided in Section 5.

2. Literature review

2.1. First-level risk assessment

Seismic risk mitigation planning for an urban area often requires a multi-level seismic risk assessment. Seismic vulnerability assessment entails identifying the structural deficiencies of a building that can prevent it from achieving performance objectives [25]. In the first-level risk assessment, the rapid visual investigation is typically performed to identify buildings that are highly vulnerable and can lead to life loss and injury in the event of an earthquake. The riskiest buildings identified in the first-level assessment are further evaluated for in-depth structural assessments. In the first-level rapid screening procedure, the seismic vulnerability of structures is evaluated by identifying the load-resisting system, seismic region, structural deficiencies, and other characteristics that influence the seismic response of the buildings [26]. Several rapid screening techniques are recommended in various standards for identifying the seismic vulnerability of buildings, such as FEMA 154, FEMA 310, ASCE 41, and Euro Code 8. Each of these methods identifies various vulnerability parameters that are responsible for the poor performance of a building. FEMA 154 is a rapid visual screening guideline to identify seismically vulnerable buildings through a walk down survey around the building by trained personnel. This process identifies parameters for the classification of buildings into seismically risky and hazardous groups [27]. FEMA 310 includes a three-tiers evaluation technique where the first tier identifies potential vulnerability factors responsible for structural, non-structural, and foundation performance [28]. ASCE/SEI 41 addresses performance-based rehabilitation of structural systems by identifying various deficiencies using prescribed checklists for structural, non-structural, and geologic hazards [25,29]. Euro Code 8 is a standard for the verification of the seismic resistance of existing buildings [30]. The evaluation process in Euro Code 8 considers the seismic vulnerability of buildings for three performance levels based on three seismic hazard levels. Other standards developed for first-level seismic risk investigation of urban buildings include National Research Council, Canada [31], and New Zealand Code [32].

Researchers have also developed simplified techniques for determining the approximated seismic performance of buildings. Benedetti and Petrini [33] proposed the *'Vulnerability Index Method'*, which is extensively used in Italy based on damage survey data. This method is further modified by several researchers (e.g., [34,35]). This approach collects data about important parameters of a building (e.g., plan, elevation, materials type, foundation type) that influence the seismic performance of the building. Mosoarca et al. [35] refined the *'Vulnerability Index Method'* using ten vulnerability parameters and applied it to evaluate historical masonry buildings' performance in Timisoara. Hassan and Sozen [36] defined the 'Priority Index' for evaluating building vulnerability using wall index (ratio of walls and infills area to total floor area) and column index (ratio of columns area to total floor area). Ozcebe et al. [37] developed a multi-level seismic vulnerability assessment procedure for reinforced concrete buildings based on a post-earthquake survey after the 1999 Düzce earthquake. Their first-level walk-down approach assigns building performance scores based on the existence of potential vulnerability parameters for prioritizing buildings that need further evaluation. This method was developed for RC moment-resisting frame buildings and is not applicable to other structural types. Lourenço and Roque [38] presented a simplified approach for the safety assessment of historical masonry buildings using simplified safety indexes (in-plan area ratio, area to weight ratio, and base shear ratio). Their method was particularly designed to evaluate the seismic performance of Portuguese churches. A first-level fuzzy--based screening procedure was developed by Demartinos and Dritsos [26] using damage information from 102 Greek buildings after the 1999 Athens earthquake. This process categorized buildings into five possible performance classes depending on the condition of structural parameters and local seismic hazard. Similarly [39], proposed a fuzzy-based visual evaluation process for reinforced concrete buildings. This technique was applied for 1249 reinforced concrete buildings located in the European part of Istanbul city, Turkey. Jain et al. [40] developed a similar rapid screening procedure for seismic performance evaluation of reinforced concrete frame buildings located in India. Formisano et al. [41] proposed a speedy seismic assessment method for historical masonry aggregates evaluating 15 vulnerability parameters. This approach was applied for assessing old URM aggregates in Italy. First-level vulnerability assessment methods are used for prioritizing buildings for further detailed structural assessments, if required for rehabilitation purposes. Although there has been notable progress in investigating the seismic performance of reinforced concrete and other building types, research focused on developing rapid first-level risk assessment techniques for old URM buildings is rare and requires further attention.

2.2. Application of fuzzy logic

Fuzzy logic has received considerable attention from researchers in many areas of civil engineering dealing with uncertainties and complex problems [42,43]. Examples of past applications of fuzzy logic in civil engineering are documented in Table 1. Fuzzy logic has become popular for defining and quantifying uncertainties in engineering systems that arise from imprecision, ambiguity, and lack of data or knowledge [50]. In first-level seismic risk assessment, expert opinion plays a significant role in prioritizing buildings through linguistic judgments [39]. Field data on seismicity, regularity, structural condition, etc., are mainly collected through a walk-down survey around the building. In this process, several risk parameters are presented in linguistic terms (e.g., yes/no, good/average/poor). Hence, collected data and assessment process are significantly dominated by subjective judgment and vagueness uncertainty [50,59]. Fuzzy logic can be used to integrate the linguistic knowledge into numerical reasoning and propagate uncertainties throughout the process [26]. It can manage uncertainty resulting from the assessment with imprecision and vagueness [60]. Therefore, this study develops a fuzzy synthetic-based first-level seismic risk evaluation technique for old URM buildings that a trained engineer/surveyor can perform through a walk-down survey. The fuzzy synthetic evaluation generates seismic risk scores for buildings, representing the possible damage scenario of the buildings in any future earthquake.

3. Proposed first-level risk evaluation model

3.1. Risk parameters

To evaluate the seismic risk of URM, it is necessary to identify all parameters and features that contribute to their vulnerability and consequence during earthquakes. The typical cause of failure of unreinforced masonry is due to the existence of a set of vulnerability parameters in the structure, such as corner separation, inadequate wall connection, high slenderness ratio, wall separation, high level of openings, incompatible distortion at re-entrant corners, etc. [61–63]. A comprehensive literature review is performed to identify a set of parameters that potentially increase the seismic risk of URM buildings. Table 2 shows various seismic risk parameters that have been considered in different assessments by various authors. In the proposed approach, wall thickness and height/length are combinedly considered as the slenderness ratio. Soil type is considered in the site seismic hazard estimation [74]. Falling hazard is typically considered as a non-structural performance parameter and is not included. Twelve most influential parameters that contributed to structural performance are selected from Table 2. Additionally, building use and occupancy are considered to account for potential consequences. It should be noted

Table 1
Application of fuzzy logic in civil engineering.

Application	Reference(s)	Description
Seismic hazard analysis	Dong et al. [44]	Applied probabilistic fuzzy information process to treat uncertainty in seismic hazard analysis.
	Boostan et al. [45]	Probabilistic seismic hazard assessment was performed using fuzzy set theory to treat existing uncertainties. Seismic hazard curve and PGA zonation map were developed in the form of iso-acceleration contour lines using fuzzy set theory.
Decision-making	Chao and Skibniewski [46]	Utilized fuzzy logic for decision making in construction technology on the basis of probabilistic cost estimation
Seismic damage assessment	Sanchez-Silva and Garcia [47]	Applied fuzzy based neural network to assess structural damage. Neural network was trained by damage data from previous earthquake.
	Fischer et al. [48]	Performed damage assessment by incorporating expert opinions and focused on uncertainty in responses. The method incorporates different types of building, soil characteristics and ground hazard.
Liquefaction prediction	Rahman and Wang [49]	Integrated fuzzy neural networks trained with two stage algorithm with large database of liquefaction case studies for the assessment liquefaction potential of a site.
Rapid visual screening	Demartinos and Dritsos [26]	Fuzzy membership is used to categorized vulnerability parameters into different performance grades and adaptive neuro fuzzy inference system was used to categorized into different damage grades.
Seismic performance evaluation	Tesfamariam and Saatcioglu [50]	Developed a hierarchical seismic risk evaluation method incorporating seismic hazard, building vulnerability and consequence of failure in the fuzzy AHP and validated the method with observed damage data.
	Sadrykia et al. [51]	Proposed a GIS-based model with the integration of Analytical Hierarchy Process (AHP) and fuzzy sets theory. This approach was applied for a municipality to determine seismic performance.
Structural vibration control	Guclu and Yazici [52]	Proposed fuzzy logic and PID controller for MDOF system to control structural vibration induced by earthquake considering non-linear soil-structure interaction.
Risk assessment of bridges	Wang and Elhag [53]	Multi-criteria group decision making for the treatment of uncertainty in bridge risk assessment. Incorporated experts opinions and proposed two algorithm justified through case studies.
Risk management of railways	An et al. [54]	Incorporated fuzzy reasoning approach and AHP in terms of failure frequency, consequence severity and probability in the railway risk management.
Road maintenance	Štemberk et al. [55]	Durability analysis was performed based on fuzzy logic for concrete slab bridge based on stiffness reduction of concrete for the combined effect of cyclic loading, freeze-thawing and chloride contamination.
Underground risk assessment	Fayaz et al. [56]	Proposed hierarchical fuzzy inference for determining risk of underground infrastructures (e.g. electrical, water network). Proposed hierarchical structure introduced maximum and average bases for reducing the number rules.
Landslide hazard map	Razifard et al. [57]	GIS based multi-criteria decision making based on fuzzy model to develop landslide hazard map.
Geotechnical Risk Analysis	Liu et al. [58]	Implemented a fuzzy-based Bayesian framework with the integration of Support Vector Machine for seismic damage analysis of slopes.

Table 2
Seismic risk parameters of URM.

Reference (s)	Risk Parameters: No. of Storey	Wall Thickness	Length of Wall	Height of Wall	Wall Opening	Quality of Material	Connection Between Walls	Connection Between Wall and Roof	Horizontal Band	Plan Regularity	Vertical Regularity	Pounding	Year Built	Falling Hazard	Site Seismicity	Soil Type	Deterioration and Damage
FEMA 154 [27]	✓	x	x	✓	x	x	x	✓	x	✓	✓	✓	✓	✓	x	✓	x
Arya [64]	x	✓	✓	✓	✓	x	x	x	✓	✓	✓	x	x	✓	x	✓	x
Arya et al. [65]	x	x	x	x	✓	✓	✓	✓	✓	✓	✓	x	x	x	x	x	x
Achs and Adam [66]	x	x	x	x	x	x	x	x	✓	✓	✓	x	x	✓	✓	✓	x
Vicente et al. [67]	✓	x	✓	x	✓	x	x	x	✓	✓	✓	x	x	x	x	✓	x
Barrantes [68]	x	x	x	x	x	x	x	x	x	✓	✓	x	✓	x	✓	✓	✓
Tassios et al. (2008)	✓	✓	✓	x	✓	✓	✓	x	x	x	x	✓	x	x	✓	✓	✓
Restrepo-Velez and Magenes [69]	x	x	✓	x	x	x	x	x	✓	✓	✓	x	x	x	✓	x	x
Doğangün et al. [70]	x	x	x	x	✓	✓	x	✓	✓	✓	✓	x	x	x	x	x	x
Erberik [4]	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	x	x	x	x	x	x	x
Sinvhal [71]	x	x	x	x	x	x	✓	✓	✓	x	x	✓	x	x	x	x	x
Ulrich et al. [72]	x	x	x	x	x	x	✓	x	x	✓	✓	✓	x	x	x	x	x
Ural et al. [72]	x	✓	x	x	x	✓	✓	✓	x	x	X	x	x	x	x	x	x
Mishra [73]	x	x	✓	x	✓	x	x	x	✓	✓	✓	x	x	x	x	x	x

* Note: √: considered in the study; x: not considered.

that ‘type of foundation’ is not considered as a risk parameter in this study as foundations are rarely visible and often impossible to recognize during the rapid visual inspection process. Also, URM buildings located in the same region and geologic conditions would likely have the same foundation types. Hence, it was assumed that the foundation type would have less influence in estimating the relative seismic risk of old URM buildings in the same region. Hence, in the proposed approach, 14 most influential risk parameters are considered for seismic risk evaluation of URM buildings. The details of performance indicators are discussed in the next sections.

3.2. *Fuzzy synthetic structure*

The theory of fuzzy logic was first proposed by Zadeh [60] for transforming linguistic variables into quantitative reasoning. This is a strong tool that accommodates both linguistic data (expert knowledge) and numerical data into the same fuzzy hierarchical structure. The basis of fuzzy membership representation is developed from traditional set theories. The fuzzy membership function, μ, maps a variable’s linguistic or numerical values into fuzzy membership values [0,1] [26,60]. A synthetic fuzzy evaluation is utilized to evaluate the seismic risk of a given building based on multiple input parameters. The risk aggregation of fuzzy membership values of risk classes is performed through a fuzzy synthetic technique. The fuzzy hierarchical structure has two levels, as illustrated in Fig. 1. The selected fourteen risk parameters in the first layer are classified into five indexes for estimating the risk score of a building. The fuzzy synthetic approach has four steps to evaluate the seismic risk of buildings: 1) fuzzification of risk parameters; 2) weight generation using the analytical hierarchy process; 3) fuzzy membership transformation; 4) risk aggregation, and 5) defuzzification.

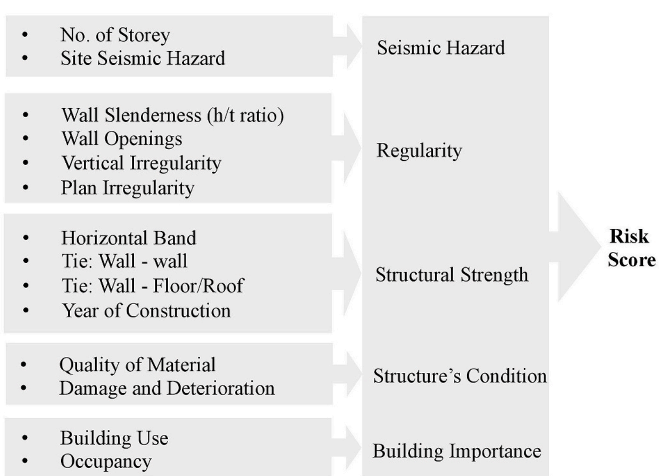

Fig. 1. Fuzzy hierarchical structure.

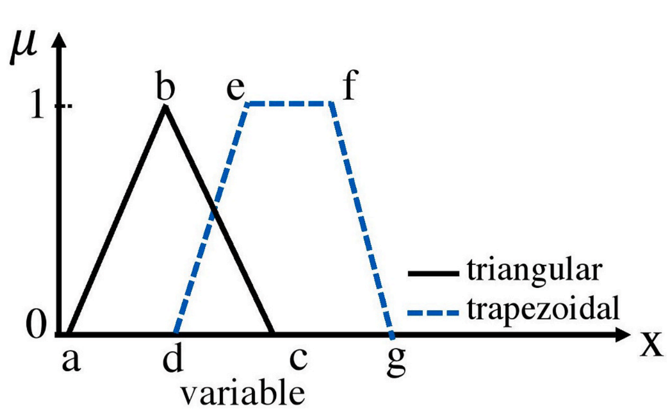

Fig. 2. Fuzzy membership functions.

3.3. *Fuzzification of risk parameters*

The seismic risk is classified into five classes: very low, low, moderate, high, and very high tagged as VL, L, M, H, and VH, respectively. To assign values of these linguistic risk classes for each input parameter, fuzzy membership functions are required. Fuzzy membership functions can be defined in various ways, such as triangular, trapezoidal, Gaussian, singleton, etc. Here, the membership functions for the five risk classes are defined using either triangular or trapezoidal membership functions. Membership functions are defined over the possible range of each parameter, based on literature review and expert judgment. Fig. 2 shows generalized triangular and trapezoidal membership functions.

Fuzzy memberships of triangular and trapezoidal functions can be expressed by Equations (1) and (2), respectively, as follows:

$$\mu(x)_{tri} = \begin{cases} 0; x < a \\ \dfrac{x-a}{b-a}; a \le x \le b \\ \dfrac{x-c}{b-c};\ b \le x \le c \\ 0;\ x > c \end{cases} \tag{1}$$

$$\mu(x)_{trap} = \begin{cases} 0;\ x < d \\ \dfrac{x-d}{e-d};\ d \le x \le e \\ 1; e \le x \le f \\ \dfrac{x-g}{f-g}; f \le x \le g \\ 0;\ x > g \end{cases} \tag{2}$$

where $\mu(x)$ is the fuzzy membership value and is estimated depending on the input parameter value, mapped on the x-axis. In equation (1), a, b and c are the minimum, the most likely, and the maximum values of a triangular membership function, respectively. Similarly, in equation (2), d is the minimum value, [e, f] is the most likely interval, and g is the maximum value of a trapezoidal membership function.

The 14 parameters that contribute to the overall seismic risk under the five indexes shown in Fig. 1 and their corresponding membership functions are discussed below.

3.3.1. *Seismic hazard index*

3.3.1.1. No. of storey. The height of a masonry building is an important seismic performance indicator. Taller buildings undergo larger deformation during earthquakes resulting in damage. Various building codes restricted the construction of taller masonry buildings in regions of high seismicity. The Turkish Earthquake Code [75] allows a maximum of 2, 3, and 4-storey masonry construction in high, moderate, and low seismic zones, respectively. Mexican Building Codes suggested that a masonry building should not be taller than 13 m or five stories [76]. In this study, fuzzy memberships of the number of storey are defined as shown in Fig. 3(a).

3.3.1.2. Site seismic hazard. Fuzzification of seismic hazard for the masonry buildings is calculated following Tesfamariam and Saatcioglu [12,50]. The seismic hazard at a building site can be estimated based on the information of design spectra, soil type, and fundamental period of a building. The level of seismic hazard is estimated based on the spectral acceleration S_a (T), which is estimated based on building design spectra. The influence of soil type variability is accounted for while selecting the type of building spectrum, as shown in Fig. 3(b). The fundamental

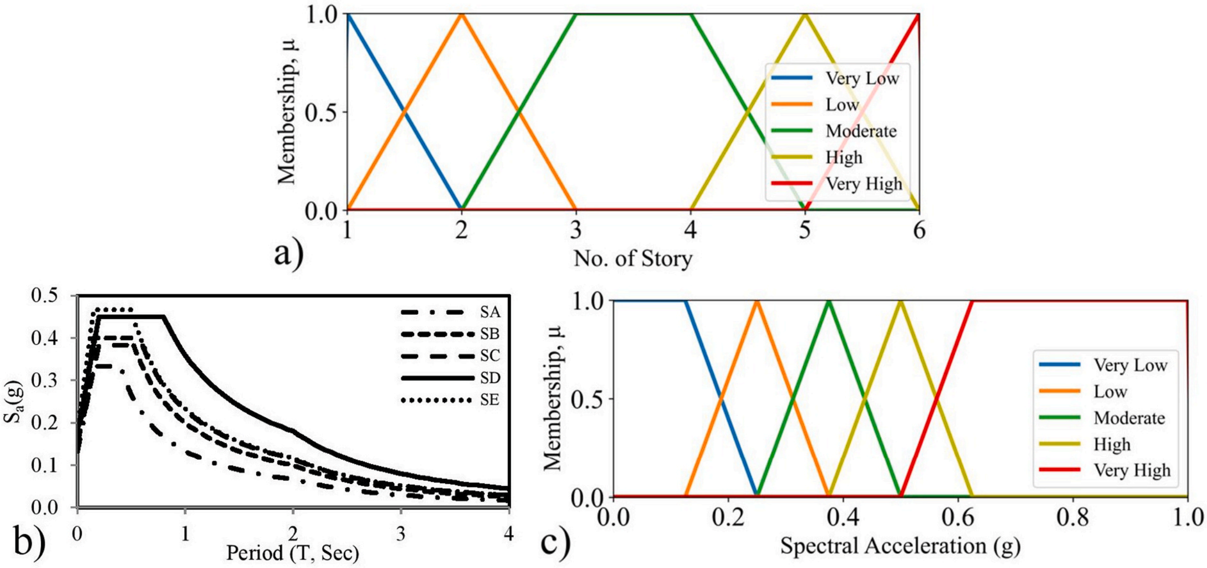

Fig. 3. a) Fuzzy memberships for no. of storey; b) design spectra and c) fuzzy memberships for spectral acceleration.

Fig. 4. Damage around openings in masonry walls; a) diagonal cracks after 2001 Bhuj earthquake [9] and b) stress concentration and damage due to irregularity of openings after 2009 L'Aquila earthquake [82].

building period for masonry buildings is estimated using the Bangladesh National Building Code [74]. Fuzzy memberships of spectral acceleration are shown in Fig. 3(c).

3.3.2. Regularity index

3.3.2.1. Wall slenderness. Wall slenderness is one of the most important seismic performance indicators of masonry structures [63]. Wall thickness should be adequate to resist shear strength [77]. Wall having a lower thickness, i.e., higher slenderness ratio, will have less resistance to shear failure during earthquake loading and increase the susceptibility of in-plane shear failure with diagonal shear cracks [2,63,78]. For a given height to thickness ratio (h/t), Bariola et al. [79] showed that a thicker wall performs well against strong ground shaking. Design standards (e.g., Euro Code 6 [80], ASCE/SEI 41–17) provide a guideline for the minimum required wall thickness and wall slenderness limit for designing masonry walls. Sharif et al. [81] assessed h/t limits for masonry walls and found that higher slenderness increases the probability of collapse of a wall.

3.3.2.2. Opening in the wall. The presence of openings in masonry walls increase vulnerability against strong ground shaking [5]. Parisi and Augunti [82] examined the performance of irregular masonry walls with various opening sizes and opening positions. The presence of irregular openings in the masonry wall results in non-uniform distribution of gravity loads and seismic forces and leads to premature collapse [82]. An increase in opening size increases stress concentration at the corner of the opening and initiate cracks in the wall [2,83]. Fig. 4 shows observed damage around the masonry wall openings after past earthquakes.

It is important to have a sufficient load-bearing wall (excluding opening and doors) in comparison to the total gross floor area for reducing the seismic vulnerability of masonry walls. Various standards provide guidelines to design wall openings in masonry buildings. For instance, the Turkish Earthquake Code recommends the length of openings should not exceed 40% of the total length, and spacing between openings should be larger than 1 m in the high seismic region [75]. An opening area less than 10% of the total wall area will not significantly reduce the resistance of masonry walls in comparison to walls without having masonry infill in it.

3.3.2.3. Vertical irregularity. Irregularity in buildings can cause an adverse effect on seismic performance [84,85]. Vertical irregularities (VI) consist of abrupt changes in stiffness and strength along with the building height, which is one of the major factors for structural damage during a strong earthquake [12,50]. VI arises due to irregular mass distribution between storey levels, irregular vertical geometric configurations such as setbacks, and discontinuity in the lateral force-resisting elements. Irregularity due to soft storey, weak storey, and setback increase seismic vulnerability [86,87]. Soft storey and weak storey occur due to a large difference in lateral force resisting system stiffness and strength change, respectively, in between floor levels [28]. A good design practice should avoid abrupt changes in this load path so that localized stress concentrations are avoided. The influence of an irregularity varies with the degree of severity, which depends on the extent of the irregularity in the structure. The level of vertical irregularity can be determined linguistically by the judgment of the structural engineer during a walk down survey for the transformation and fuzzification purposes. Five triangular fuzzy membership functions are selected to represent the vertical irregularity parameter. In field investigations, the presence of VI in a building can be expressed by yes/no operator.

3.3.2.4. Plan irregularity. Previous earthquakes revealed that Plan Irregularity (PI) has an adverse effect on the vulnerability to seismic loads [6,61,62]. PI arises from asymmetric plan configurations generated by large eccentricities between the centre of mass and centre of resistance of a structure. PI increases building vulnerability to torsion as well as the potential area of high-stress concentration. Re-entrant corner buildings are prone to torsion and stress concentration [40]. The torsional effect is relatively higher during dynamic seismic loading, which may lead to the overturning of structural elements [50]. Similar to VI, linguistic value for PI should be chosen by field engineers based on the building configuration.

Fig. 5 shows the fuzzy memberships of regularity index parameters (wall slenderness, opening in walls, VI, and PI).

3.3.3. Structural strength index

3.3.3.1. Horizontal band. Masonry buildings perform better in resisting seismic loadings if box-type behavior can be ensured. Including a horizontal band in masonry design ensures box-like response during strong ground shaking [2]. Without a horizontal band, masonry walls cannot gain in-plane integrity, and thus out-of-plane failure may occur [88,89]. According to the Turkish Earthquake Code [75], each seating length of the window and door lintels on the walls shall not be less than 15% of clear lintel span or less than 200 mm, whichever is greater. If reinforced concrete bond beams are used, width shall be equal to the width of the wall, and height shall not be less than 200 mm.

3.3.3.2. Connection between walls. The connection between walls can control the out-of-plane deflection of the floors [2,89]. Lack of connection between walls can result in severe damage to masonry buildings during an earthquake [62,88]. If connections between walls are inadequate, out-of-plane failure can occur, which can lead to serious damage to the walls [90].

3.3.3.3. Connection between wall and floor/roof. A proper connection between wall and floor can enable a building to respond in a box-like action and resist in-plane loading during seismic excitation [2,89]. The connection between walls and floor can control the out-of-plane deflection of the floors [2,89]. Also, an adequate connection between walls and the roof is essential for desirable seismic performance [2]. An inadequate connection between wall and roof can cause the overturning of walls and out-of-plane failure [2,62]. The shear strength of the wall can be increased through a proper connection between walls and roof [77].

3.3.3.4. Year of construction (age). The year of construction (or age) is an important indicator of the seismic performance of masonry buildings. A good example of the effect of year of construction is failures associated with lack of column confinement and appropriate seismic detailing. During site investigations, original design drawings may not be readily available. Year of Construction can be used to infer important information about the seismic design code provision and, consequently, information about ductility, strength, and level of detailing relevant to the era during which the building was constructed.

Fig. 6 shows fuzzification for parameters of the structural strength index.

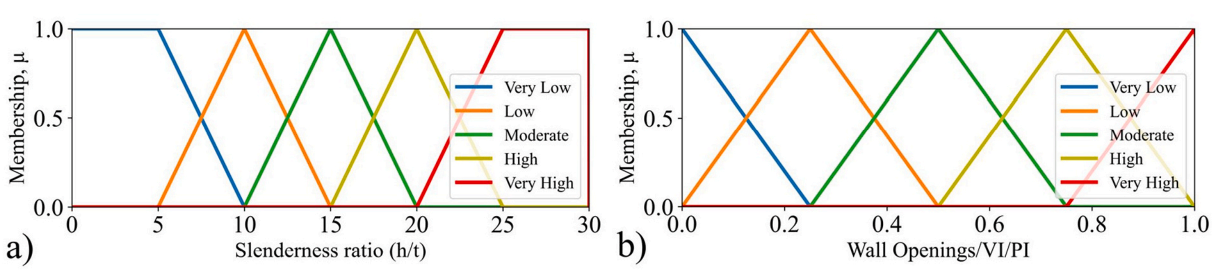

Fig. 5. Regularity index: a) slenderness ratio; b) wall openings/VI/PI.

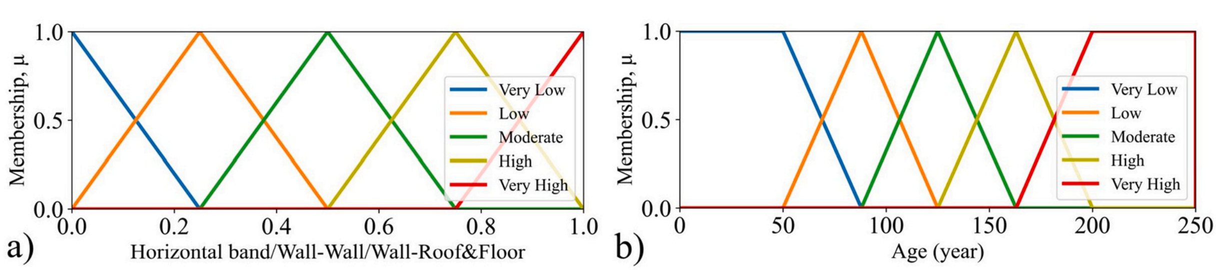

Fig. 6. Fuzzy membership for structural strength index: a) horizontal band/connection between walls/connection between wall and floor/roof; and b) building age.

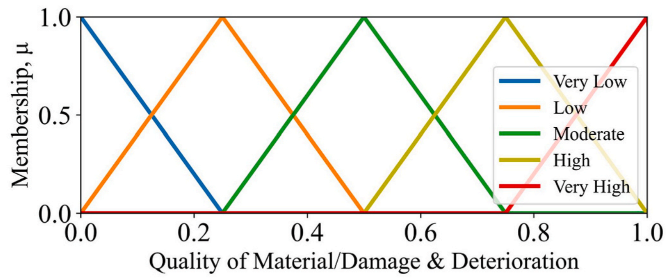

Fig. 7. Fuzzy membership for structural condition index.

3.3.4. Structural condition index

3.3.4.1. Quality of material. The quality of materials of masonry buildings is an important factor that affects seismic performance [7,62]. It has been observed in past earthquakes that poor quality materials have led to inadequate seismic performance of masonry buildings [61, 85]. Poor quality materials may lead to brittle failure in masonry structures during earthquake loading [6].

3.3.4.2. Existing damage and deterioration. The existence of damage and deterioration in load-bearing masonry can adversely affect the seismic performance of a building. Hence, existing damage and deterioration should be accounted for in predicting the seismic performance of URM buildings. The presence of damage and deterioration is measured by yes/no operator.

Fig. 7 shows fuzzification for parameters included in the structural condition index.

3.3.5. Building importance index

3.3.5.1. Building use. Special consideration is given to important structures in design. Design code guidelines classify buildings into various groups based on their use and relevant importance during and after earthquakes. Buildings that are critical to post-earthquake recovery (e.g., hospital, fire station) are given a higher level of priority. Government and public facilities, schools, etc. are given the second level of priority. Residential and other types of buildings typically fall into the lower level of importance categories.

3.3.5.2. Occupancy. The number of occupants in a building is a good indicator of possible casualty in case of building damage during an earthquake. Higher casualties are expected if a higher number of occupants live in the damaged building.

Fig. 8 shows fuzzy memberships for parameters in building importance index.

3.4. Fuzzification transformation

A heuristic approach is used to transform input parameter's value into five linguistic risk classes. Triangular fuzzy number (TFN) is defined to represent qualitative input parameters (e.g., vertical irregularity, plan irregularity) based on expert opinion. TFN is denoted by three vertices (α, β, γ) where α, β and γ refers to the minimum, most likely, and maximum numbers, respectively [12], as expressed by Fig. 9. TFN of an input parameter is then mapped on fuzzy memberships to obtain intersected values of linguistic risk classes. For instance, for a TFN (α, β, γ) in Fig. 9, intersected values of risk classes are obtained by mapping fuzzy TFN on membership functions. If TFN intersects a particular fuzzy member more than once, the maximum value is considered. The fuzzified risk classes values are given as below:

$(\mu_{VL}, \mu_L, \mu_M, \mu_H, \mu_{VH}) = (0.45, \max[0.63, 0.90], 0.15, 0, 0) \Rightarrow (0.45, 0.90, 0.15, 0, 0)$

The granularity of fuzzy memberships of risk parameters is expressed in Figs. 2–8 whereas TFN values are assigned based on expert judgment and previous studies (e.g. [12]). Table 3 shows TFN, the fuzzy transformation of the qualitative variables and the range of quantitative parameters used in this study. The field survey assigns a TFN for the linguistic parameter based on the observed condition of the surveyed building. For example, if vertical irregularity is present in a building, TFN for vertical irregularity is assigned as 'Yes:(0.50, 0.85, 0.95)' and corresponding transformed fuzzification for risk classes is assigned as (0, 0, 0.30, 0.80, 0.50).

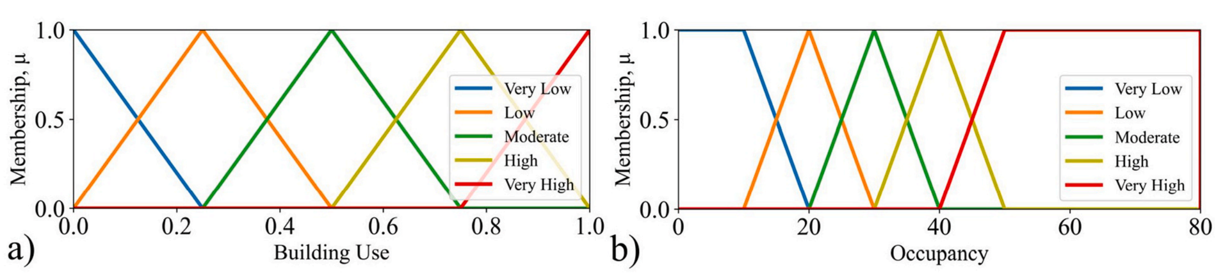

Fig. 8. Fuzzy membership for building importance index: a) building use and b) occupancy.

$$
\mu_{TFN} = \begin{cases} 0, & 0 \le x \le \alpha \\ \dfrac{x-\alpha}{\beta-\alpha}, & \alpha \le x \le \beta \\ \dfrac{\gamma-x}{\gamma-\beta}, & \beta \le x \le \gamma \\ 0, & x \ge \gamma \end{cases}
$$

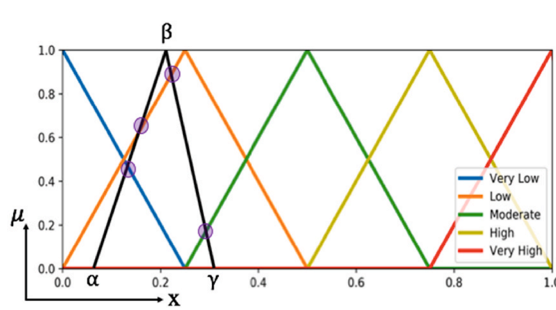

Fig. 9. TFN representation on Fuzzy membership.

Table 3
Transformation of linguistic inputs.

Parameter	Linguistic Observation /Quantitative Range	TFN (α, β, γ)	Fuzzification (μ_{VL}, μ_L, μ_M, μ_H, μ_{VH})
Seismic Hazard			
No. of storey	[1, 6]	–	
Seismic hazard	[0, 1.0]	–	
Regularity			
Slenderness ratio	[0, 30]	–	
Opening in walls	Low	(0.10, 0.20, 0.30)	(0.43, 0.86, 0.14, 0, 0)
	Moderate	(0.40, 0.50, 0.60)	(0, 0.29, 1.00, 0.29, 0)
	High	(0.70, 0.80, 0.90)	(0, 0, 0.14, 0.86, 0.43)
Vertical irregularity	Yes	(0.50, 0.85, 0.95)	(0, 0, 0.30, 0.80, 0.50)
	No	(0.10, 0.15, 0.40)	(0.57, 0.80, 0.30, 0, 0)
Plan irregularity	Yes	(0.50, 0.85, 0.95)	(0, 0, 0.30, 0.80, 0.50)
	No	(0.10, 0.15, 0.40)	(0.57, 0.80, 0.30, 0, 0)
Structural Strength			
Horizontal band	Yes	(0.10, 0.15, 0.40)	(0.57, 0.80, 0.30, 0, 0)
	No	(0.50, 0.85, 0.95)	(0, 0, 0.30, 0.80, 0.50)
Connections between walls	Yes	(0.10, 0.15, 0.40)	(0.57, 0.80, 0.30, 0, 0)
	No	(0.50, 0.85, 0.95)	(0, 0, 0.30, 0.80, 0.50)
Connections between wall-floor	Yes	(0.10, 0.15, 0.40)	(0.57, 0.80, 0.30, 0, 0)
	No	(0.50, 0.85, 0.95)	(0, 0, 0.30, 0.80, 0.50)
Age	[0, 250]	–	
Structural Condition			
Quality of material	Good	(0.10, 0.20, 0.30)	(0.43, 0.86, 0.14, 0, 0)
	Moderate	(0.40, 0.50, 0.60)	(0, 0.29, 1.00, 0.29, 0)
	Poor	(0.70, 0.80, 0.90)	(0, 0, 0.14, 0.86, 0.43)
Existing damages	Low	(0.10, 0.20, 0.30)	(0.43, 0.86, 0.14, 0, 0)
	Moderate	(0.40, 0.50, 0.60)	(0, 0.29, 1.00, 0.29, 0)
	High	(0.70, 0.80, 0.90)	(0, 0, 0.14, 0.86, 0.43)
Important Index			
Building Use	Ordinary building	(0.70, 0.80, 0.90)	(0, 0, 0.14, 0.86, 0.43)
	Important public buildings	(0.40, 0.50, 0.60)	(0, 0.29, 1.00, 0.29, 0)
	Critical buildings (e.g. medical)	(0.10, 0.20, 0.30)	(0.43, 0.86, 0.14, 0, 0)
Occupancy	[0, 100]	–	

3.5. Analytical hierarchy process

At each level of the hierarchy of the structure in Fig. 1, the relative importance of risk parameters is required to aggregate input parameters into a single output. The relative importance of parameters is taken based on knowledge-based expert judgment. An expert survey on researchers who have expertise in seismic risk evaluation of masonry buildings was conducted to assign weights of parameters. The experts were asked to assign a weight to each risk parameter and index in the fuzzy hierarchical structure based on parameters and indexes relative contribution to the overall seismic risk. The response rate was 60% from a sample size of 20 experts. The analytical hierarchy process (AHP) is then performed to evaluate the relative importance of parameters in each of the five indexes. Experts' opinions are utilized in the AHP to assign weights to the parameters. Based on the surveyed experts' opinions, weights of risk indexes (W_i) and weight of risk parameters (w_i) are assigned. The decomposed weight (DW_i) is estimated by multiplying the weight of risk index (W_i), and the weight of risk parameter (w_i). Table 4

Table 4
AHP weights.

Main Index	W_i	Parameter	Weight (w_i)	Decomposed weight $DW_i = (W_i \times w_i)$
Seismic Hazard	**0.25**			
		No. of storey	0.39	0.10
		Seismic hazard (S_a)	0.61	0.15
Regularity	**0.20**			
		Slenderness ratio	0.25	0.05
		Opening in walls	0.24	0.05
		Vertical irregularity	0.25	0.05
		Plan irregularity	0.26	0.05
Structural Strength	**0.24**			
		Horizontal band	0.26	0.06
		Connections between walls	0.28	0.07
		Connections between wall-floor	0.28	0.07
		Age	0.18	0.04
Structural Condition	**0.20**			
		Quality of material	0.46	0.09
		Existing damages	0.54	0.11
Important Index	**0.11**			
		Building Use	0.52	0.06
		Occupancy	0.48	0.05

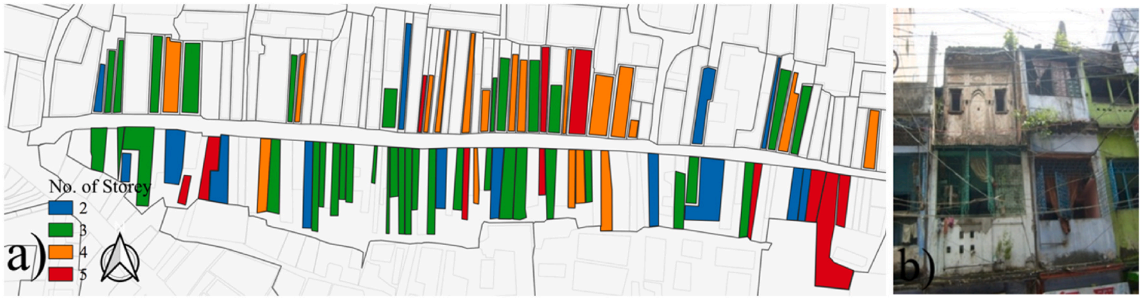

Fig. 10. a) Layout of buildings, and b) an example of building elevation view.

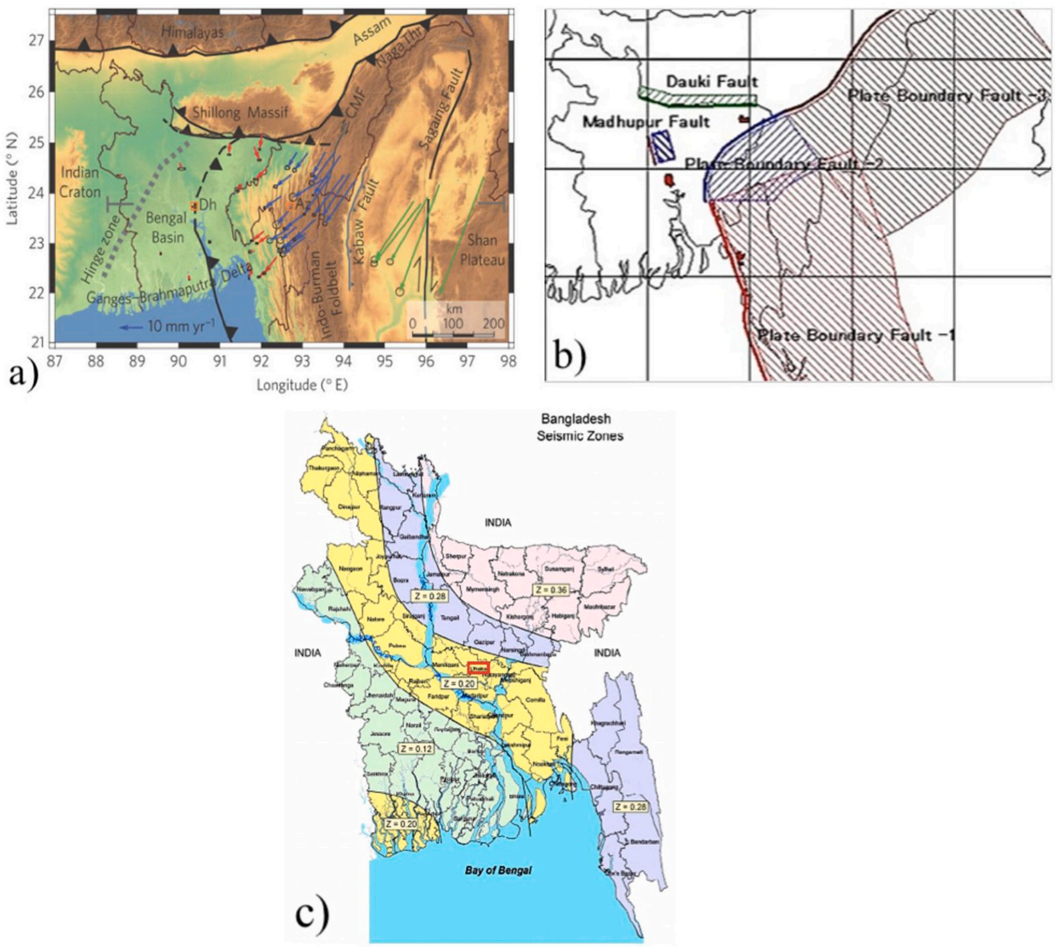

Fig. 11. a) Active megathrust beneath Ganges delta & Indo-Burman ranges [94]; b) Faults in Bangladesh [96]; c) Seismic Zonation Map [74].

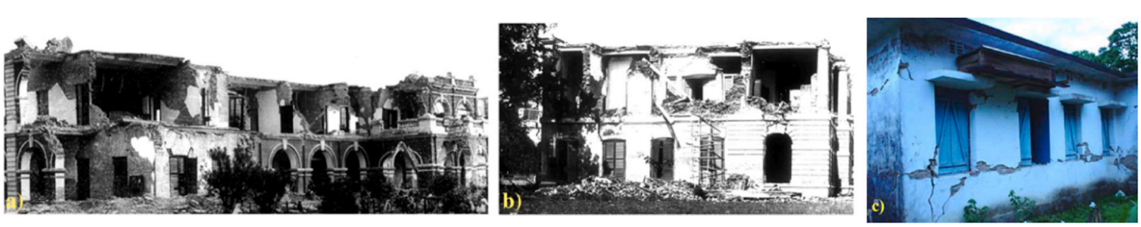

Fig. 12. Damage to masonry buildings: a) Judge's Cutcherry at Mymensingh; b) Judge's House at Rangpur after 1897 Great Indian Earthquake (Source: NISEE) and c) Medical facility building after 2003 Barkal Earthquake (Source [95].

Fig. 13. URM buildings: a) cluster view; b) open courtyard; c) roof; d) openings; e & f) cracks; and g & h) deterioration in bearing wall.

Table 5
Summary of field statistics.

Risk Index	Risk Parameter	Observed Data				Unit
Seismic Hazard	No. of Storey	2 storey building: 14		3 storey building: 37		nos.
		4 storey building: 19		5 storey building: 11		nos.
	Site Seismic Hazard (Sa)	Maximum: 0.31		Minimum: 0.29		g
Regularity	Slenderness Ratio (SR)	8.1≤SR ≤ 12: 10		12<SR ≤ 16: 11		–
		16<SR ≤ 20: 11		20<SR ≤ 24: 18		–
		24<SR ≤ 27.4: 31				–
	Opening in Wall	Low: 74	Moderate: 7		High: 0	nos.
	Vertical Irregularity	Yes: 35		No: 46		nos.
	Plan Irregularity	Yes: 67		No: 14		nos.
Structural Strength	Horizontal Band	Yes: 10		No: 71		nos.
	Connection Between Wall	Yes: 52		No: 29		nos.
	Connection Between Wall and Floor/Roof	Yes: 35		No: 46		nos.
	Age (Year)	<100: 19	100–150: 19		>150: 43	nos.
Structural Condition	Quality of Material	Good: 0	Moderate: 6		Poor: 75	nos.
	Existing Damages	Low: 2	Moderate: 0		High: 79	
Importance	Building Use	Ordinary: 81	Important:0		Critical facility: 0	nos.
	Occupancy	0–20 per.: 16	20–30 per.: 16		30–40 per: 19	nos.
		40–60 per.: 18	60–80 per.: 6		80–120 per.: 6	nos.

Note: nos.: no. of buildings, per: persons.

shows the weights of parameters assigned using AHP. The summation of weights in each layer is equal to unity (i.e. $\sum_{i=1}^{n} w_i = 1.0, \sum_{i=1}^{n} DW_i = 1.0$).

3.6. Risk aggregation

Fuzzy membership values and weights are used to aggregate the input parameters into a single input, as below:

$$(\mu_{VL}, \mu_L, \mu_M, \mu_H, \mu_{VH})_i = (DW_1, DW_2, DW_3.....DW_n) \times \begin{bmatrix} \mu_{VL}{}^1 & \cdots & \mu_{VH}{}^1 \\ \vdots & \ddots & \vdots \\ \mu_{VL}{}^n & \cdots & \mu_{VH}{}^n \end{bmatrix} \tag{3}$$

where μ and DW represent fuzzy membership number and decomposed weight of parameter, respectively. The dimension of the weight vector and fuzzy membership matrix for a building are (1 × n) and (n × 5), respectively, whereas n is the number of parameters (i.e. n = 14 in this case). Using equation (3), the fuzzification value for different levels of risk (very low to very high) is finally obtained for a building.

3.7. Defuzzification

The defuzzification process is used to convert the fuzzy output number into a crisp risk value. There are several ways to perform the defuzzification process (e.g., centre of the area, centre of max, and mean of max, weighted average). The weighted average method is applied in this study to determine the crisp number, as expressed below:

$$\text{Risk} = \sum_{i=1}^{m} q_i \times \mu_i \tag{4}$$

where, q_i is quality ordered weights [0, 5], μ is the fuzzy membership and m is the number of risk levels (i.e. m = 5 in this case). The q_i values assigned for the five different levels of risk are $q_{VL} = 1$, $q_L = 2$, $q_M = 3$, $q_H = 4$, $q_{VH} = 5$.

4. Case study

The proposed fuzzy-based first-level seismic risk assessment method was applied for the old URM buildings located in the older part of Dhaka city, Bangladesh. A large proportion of urban buildings in Bangladesh

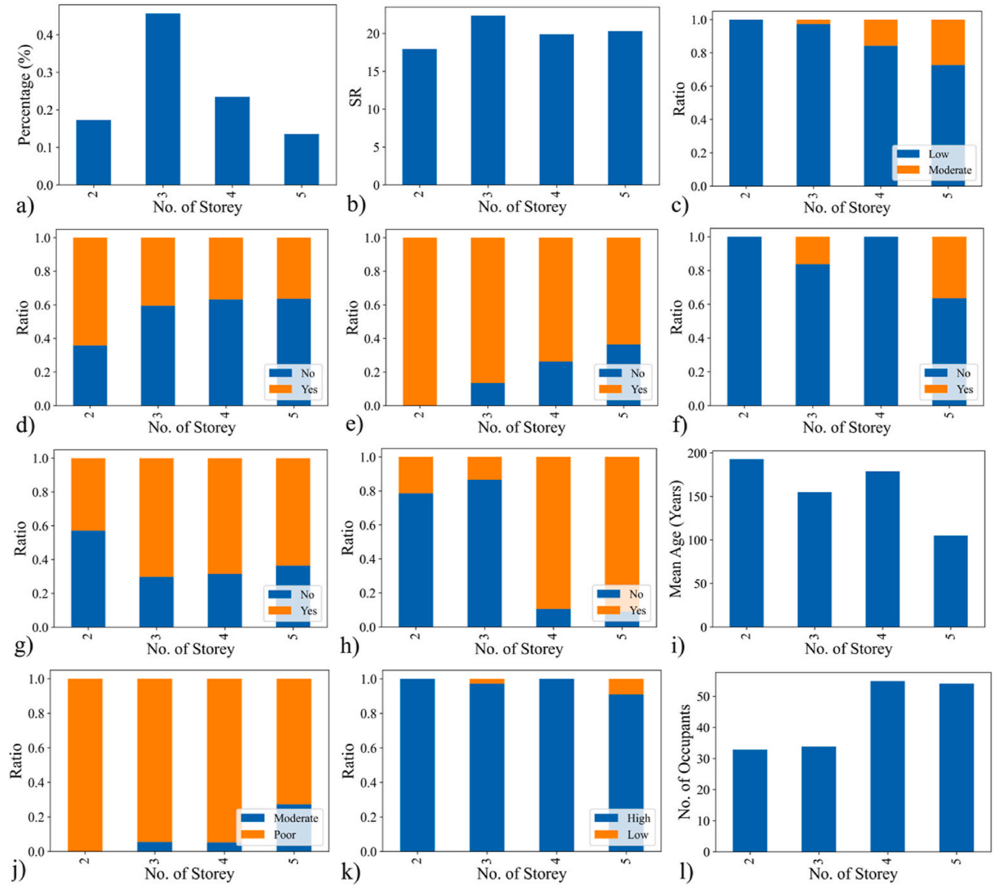

Fig. 14. Risk parameters: a) No. of storey; b) wall slenderness; c) opening in walls; d) vertical irregularity; e) plan irregularity; f) horizontal band; g) connection between walls; h) connection between wall and floors/roof; i) mean age; j) quality of material; k) existing damage level; l) occupancy.

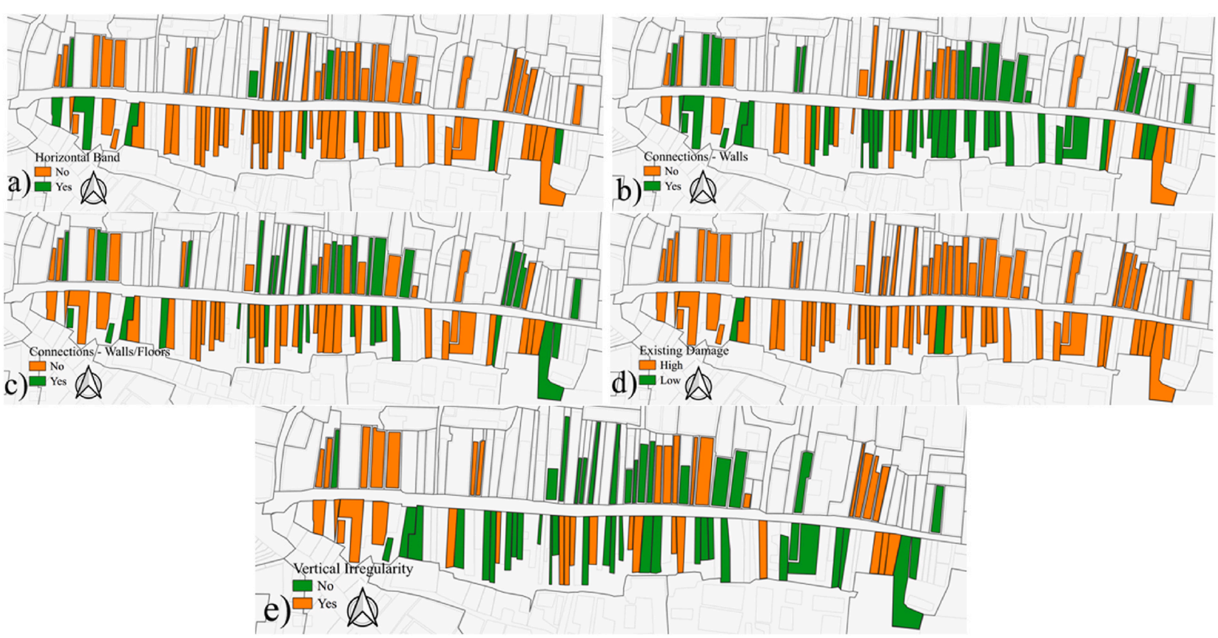

Fig. 15. Risk parameters for Shakhari Bazar: a) horizontal band, b) connections between walls, c) connections between walls and floors, d) existing damages, and e) vertical irregularity.

Table 6
Example building data.

Parameter Name	Weights	Sample Building (B-19)	
		Parameter Value	Transformed Fuzzification
No. of storey	0.10	4	(0, 0, 1, 0, 0)
Seismic hazard	0.15	0.31	(0, 0.56, 0.44, 0, 0)
Slenderness ratio	0.05	10.5	(0, 0.9, 0.1, 0, 0)
Opening in walls	0.05	Low	(0.43, 0.86, 0.14, 0, 0)
Vertical irregularity	0.05	No	(0.57, 0.80, 0.30, 0, 0)
Plan irregularity	0.05	Yes	(0, 0, 0.30, 0.80, 0.50)
Horizontal band	0.06	No	(0, 0, 0.30, 0.80, 0.50)
Connections: walls	0.07	No	(0, 0, 0.30, 0.80, 0.50)
Connections: wall-floor	0.07	Yes	(0.57, 0.80, 0.30, 0, 0)
Age	0.04	250+	(0, 0, 0, 0, 1)
Quality of material	0.09	Poor	(0, 0, 0.14, 0.86, 0.43)
Existing damages	0.11	High	(0, 0, 0.14, 0.86, 0.43)
Building Use	0.06	Ordinary	(0, 0, 0.14, 0.86, 0.43)
Occupancy	0.05	70	(0, 0, 0, 0, 1)

are made of URM. Many old URM buildings that carry the signature of historical and cultural importance have become vulnerable due to the lack of maintenance. Hence, a regional-level seismic vulnerability assessment is necessary to guide policymakers to optimize the use of resources and mitigate risk. A total of 81 URM buildings located at Shakari Bazar, an old urban settlement of Dhaka city, was selected for this study. Fig. 10(a) and (b) show the layout of the buildings with storey numbers, and an example of building elevation view at Shakhari Bazar, respectively. These buildings are representative of URM structures in the older part of Dhaka city. Most of these buildings were built under the Mughal period and later part of British rule and have become extremely vulnerable overtime [91]. Moreover, non-engineered modifications have increased the vulnerability of these old URM buildings. There is a clear need for seismic risk evaluation of URM buildings located at Shakhari Bazar.

Table 7
Sample dataset of building inventory.

Sl.	NoS	S_a	WO	VI	PI	SR	HB	C: W–W	C: W–F	Age	QM	Damage	BU	Occ	Risk Score
B-1	4	0.31	L	N	N	25.2	N	Y	Y	150	P	H	O	120	4.13
B-2	3	0.31	L	N	Y	25.2	N	Y	N	200	P	H	O	70	4.79
B-3	4	0.31	M	N	N	13.7	N	Y	Y	250	P	H	O	80	4.36
B-4	3	0.31	L	N	Y	27.4	N	N	Y	200	P	H	O	100	4.79
B-5	2	0.31	L	N	Y	12.5	N	N	Y	200	P	H	O	25	4.44
B-6	2	0.31	L	N	Y	12.9	N	N	N	200	P	H	O	95	4.64
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
B-78	4	0.31	L		Y	23.8		Y	Y	200	P	H	O	30	4.25
B-79	4	0.31	L	N	Y	22.4	N	Y	Y	150	P	H	O	35	4.21
B-80	2	0.31	L	N	Y	19.2	N	Y	N	300	P	H	O	50	4.45
B-81	5	0.31	L	N	Y	21.6	N	Y	Y	100	P	H	O	40	4.27

*P: Poor; H: High; M: Moderate; L: Low; N: No; Y: Yes; O: Ordinary; No. S: No. of Storey; WO: Wall Openings; SR: Slenderness Ratio; HB: Horizontal Band; C:W–W: Connections:Wall to Wall; C:W–F: Connections: Wall to Floor; QM: Quality of Material; BU: Building Use; Occ.: Occupancy.

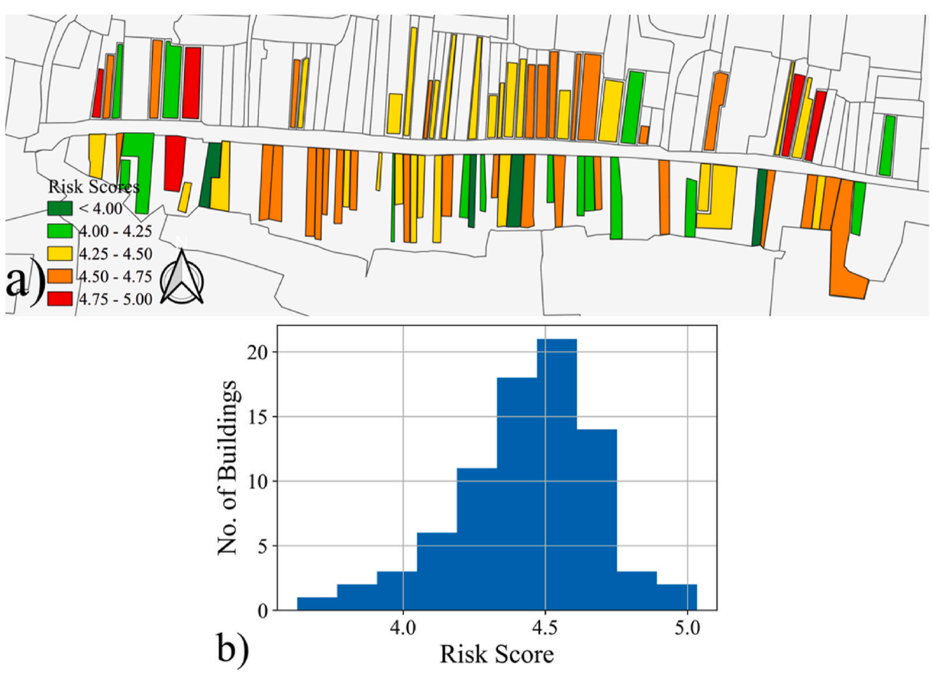

Fig. 16. Risk scores: a) map, and b) histogram.

4.1. Regional seismicity

Bangladesh is located near the junction of Indo-Australian and Euro-Asian continental plates and has experienced large earthquakes in the past [92,93]. The presence of megathrust and active faults in and around Bangladesh has been documented in recent studies [94,95]. Steckler et al. [94] detected active megathrust beneath the country and projected high locked energy underground, as shown in Fig. 11(a). CDMP [96] stated that five major faults exist that are capable of generating great earthquakes, as shown in Fig. 11(b). The Bangladesh National Building Code (BNBC) proposed a seismic hazard map that divided the country into four seismic zones based on the maximum credible earthquake of a 2% probability of exceedance in 50 years [74], as shown in Fig. 11(c). Dhaka city is located in a moderate seismic region with a zone co-efficient of 0.20g. A large percentage URM buildings were built before enforcement of the building code [95,97]. Due to the existing vulnerability in the old buildings, even a moderate size earthquake may potentially cause extensive damage to buildings, human causalities, and huge economic losses in the older part of Dhaka city.

4.2. Masonry buildings damage in past earthquakes

Extensive damage to the URM buildings was recorded in past earthquakes in Bangladesh. The 1897 Great Indian earthquake with a magnitude of M_W 8.1 is the deadliest in terms of casualties and damage in this region. An estimated European Macroseismic Scale intensity VIII was recorded for Dhaka city, and severe damage observed in a large-portion of masonry structures in Bangladesh [98]. Fig. 12(a) and (b) show severely damaged buildings located in Mymensingh and Rangpur, respectively. Many masonry buildings were significantly damaged during the 1930 Dhubri earthquake with a magnitude of M_S 7.1 [99]. Extensive damage was observed in masonry and mud buildings after the 2003 Barkal (Rangamati) earthquake. This 5.7 M_W earthquake triggered at 10 km depth from the ground surface damaged nearly 500 buildings [100]. Fig. 12(c) shows damage observed in masonry medical facility building after 2003 the Barkal Earthquake.

4.3. Field investigation and building inventory

The URM buildings located in Shakhari Bazar are made of clay brick masonry with lime mortar. These buildings stand together in a cluster on both sides of a long narrow alley, as shown in Fig. 10. Most of these old masonry buildings have load-bearing walls consisting of clay brick masonry with lime mortar. Roof framing is made of straight or diagonal lumber sheathing supported by wood joists on posts, timbers, and walls. Ties between the bearing walls and diaphragms consist of bent steel plates or government anchors set in the mortar joints and attached to framing. Unplanned non-engineered modification made it difficult to perform structural analysis. Lack of maintenance, deterioration of building materials over time, increased live load due to overpopulation, and the dead load from newly constructed upper floors are the main factors that contribute to the risk [91]. All the buildings have a high level of deterioration and cracks in the bearing walls. Fig. 13 shows the URM building conditions at Shakari Bazar. Although many of these buildings share walls with neighboring buildings in the longitudinal direction, they are considered as separate individual units.

Eighty-one (81) old URM buildings were evaluated based on the field investigation conducted by a group of trained engineers as part of a technical assessment project conducted by Dhaka City Corporation (DCC). The first author of this study was part of the data collection team. Among these buildings, about 15% (12 buildings) are modified and reconstructed a few decades earlier. Table 5 provides a summary of statistics of field investigation. Fig. 14 summarizes the distribution of risk parameters for the building inventory of Shakhari Bazar. Most of these URM buildings were initially built as two to three-storey. To meet the demand of the increasing number of occupants, these buildings were extended vertically with newly built upper floors over the years. Fig. 14(a) illustrates the distribution of the number of stories for the surveyed buildings. About 17%, 50%, 25%, and 13% of the buildings are two, three, four, and five-storey buildings, respectively. Fig. 14(b) shows that the slenderness ratio is high for all the buildings. A low to moderate level of openings in the shorter direction walls are found in these buildings. The ratio of openings is higher for the modified and vertically extended buildings, as shown in Fig. 14(c). About 43% of the buildings contain vertical irregularity, as shown in Fig. 14(d). A majority of these buildings (about 85%) have plan irregularity (narrow rectangular in shape), as illustrated by Fig. 14(e). About 12.4% of the buildings (relatively newer buildings) have a horizontal band (lintel) above the openings, as shown in Fig. 14(f). Many of these buildings have horizontal bands in the recently constructed upper floor only.

About 62.4% of the buildings have a good connection between the walls, and about 43% of the buildings have a connection between walls to floor/diaphragms. The storey-wise presence of a connection between walls and the connection between wall and floors/roof are shown in Fig. 14(g) and (h), respectively. Fig. 14(i) shows the average age of the buildings by storey numbers. Most of the old buildings are 150 years old and older, while 5-storey buildings are relatively newer, with an average age below 100 years. Based on the engineering observation, about 92.6% and 7.4% of the buildings are found to have poor and moderate material quality, respectively. The storey-wise distribution of material condition and damage levels are illustrated in Fig. 14(j) and (k), respectively. A high level of damage exists in these buildings, as shown in Fig. 13. Most of these buildings are mixed type of use (commercial shop in the ground level facing the street and residential part in the other parts/floors with an open courtyard at the rear). Hence, all the buildings are considered as ordinary buildings for the fuzzy evaluation. The number of occupants is also very high for each building. Storey-wise mean occupancy numbers are shown in Fig. 14(l).

For estimating the seismic hazard level, spectral acceleration was estimated based on the BNBC guideline [74] The soil type of Shakhari Bazar was classified as 'Class Sc' in BNBC based on the Vs30 shear wave velocity ranging from 180 to 360 m/s [74,96]. The spectral acceleration for most of these buildings is found to be 0.31g. Among the building risk parameters, some of the most influential risk parameters are also mapped into Fig. 15. Fig. 15(a), (b), 15(c), 15(d), and 15(e) show the maps for horizontal bands, connections between walls, connections between walls and floors, existing damage information, and vertical irregularity, respectively, for buildings inventory of Shakhari Bazar. The existence of horizontal bands and good connections between walls, and/or walls/floors help URM buildings perform better against earthquake loading. On the other hand, the existence of a high level of damage in walls and vertical irregularity in URM made buildings vulnerable to earthquakes.

4.4. Illustration of risk score calculation

Estimation of the risk score for buildings using fuzzy inference is illustrated with an example. Table 6 shows the properties, corresponding decomposed weights, and fuzzy membership values for the building B-19. Data obtained from the field survey is transformed into a fuzzy membership number based on the fuzzification defined in section 3.1 (as shown in Table 3). Based on the weights and fuzzy membership numbers for the fourteen (14) risk parameters as provided in Table 6, risk aggregation is performed using equation (3) from which the fuzzy membership numbers for VL, L, M, H, VH membership classes are found as 0.0899, 0.268, 0.305, 0.368, and 0.292, respectively. Finally, the risk score for the building is obtained utilizing equation (4) assigning q_i value as mention in section 3.7. Then, the final risk for the building is found to be to 4.47 which implies that the probable risk of the building to seismic hazard is high to very high.

4.5. Final risk score

A sample of the field dataset for the 81 buildings is documented in Table 7. The seismic risk of each building is estimated by evaluating 14 risk parameters through the fuzzy synthetic-based hierarchical process. Fig. 16(a) shows the risk score map for the buildings in Shakhari Bazar, whereas Fig. 16(b) shows the histogram of risk scores. It can be seen that most of the surveyed buildings are highly susceptible to earthquakes. In recent years, DCC [101] performed a technical investigation to find the seismic risk of 95 buildings (including Reinforced Concrete and URM) located at Shakhari Bazar. The study applied Rapid Visual Screening (FEMA 154), FEMA 310 and IITK-GSDMA guidelines to assess the structural integrity of the buildings under seismic hazards. The DCC [101] study reported that 22%, 42%, and 28% of the buildings are in moderate, high, and severe risk categories, respectively. As shown in Fig. 16, the risk scores obtained from the proposed approach provide similar outcomes in comparison to the study performed by DCC [101]. More than 90% of entire buildings have a risk score of more than 4.0 and are at high seismic risk.

Note that the results of this study were not compared with the other risk matrices provided by ASCE 41 [25,29] and Eurocode 8 [30], as additional information required for these approaches was not available. The application of the proposed method can be further compared with other standards (e.g., ASCE 41, Eurocode 8) in future research.

5. Conclusions

Seismic risk assessment of existing buildings is of utmost importance for prioritizing seismic rehabilitation and reducing future consequences. Most seismic risk assessment methods involve first-level risk evaluation based on simple field surveys to identify the riskiest buildings that require further assessment. In this paper, a fuzzy-based first-level risk assessment approach is presented for evaluating the seismic risk of old URM buildings. Fourteen risk parameters are classified into five indexes, and a risk score is estimated through the fuzzy synthetic-based hierarchical process. Fuzzy memberships, fuzzy transformation and weights of risk parameters are assigned based on expert opinion and literature review. The proposed approach is illustrated for an old urban settlement in Dhaka, Bangladesh. A total of 81 URM buildings are evaluated, and the performance of the method was compared with a previous study. The proposed approach shows promising outcomes and can be applied in risk assessment of URM buildings with similar configurations. Future research can focus on validating the proposed method using damage data collected in past or future earthquakes.

Author statement

Ram Krishna Mazumder: Conceptualization, Methodology, Data collection, Modeling, Analysis, Writing – original draft. Sohel Rana: Data curation, Analysis, Writing – original draft. Abdullahi Salman: Investigation, Writing – reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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