Rapid Seismic Assessment Method for Unreinforced Masonry Buildings in Bangladesh

by

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MASTER OF SCIENCE IN CIVIL ENGINEERING

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Recommendation of the Board of Examiners

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It is hereby confirmed that this thesis and the studies embodied in it are the result of the analysis carried out by the author under the supervision of Dr. Md. Tarek Uddin, PEng., Professor, Department of Civil and Environmental Engineering, Islamic University of Technology, Gazipur, Bangladesh and the co-supervision of Dr. Md. Abdur Rahman Bhuiyan, Professor, Department of Civil Engineering, Chittagong university of Engineering and Technology, Chittagong. Wherever contributions of others were involved, every effort has been made to indicate this clearly with due reference to the literature and acknowledgement of collaborative research and discussions. Neither thesis nor any part of it has been submitted to or is being submitted to for any other purposes (except for publication).

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Dedication

I dedicate this thesis to my beloved wife!

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List of Notations

τ_{wi}	Average shear strength of individual masonry wall
A_{wi}	In-plane cross-sectional area of the wall
C_a	Response acceleration
D_s	Reduction factor considering building ductility
W	Total building weight (including both dead loads and live loads)
N_s	Number of storeys
A_f	Floor area
w	Unit weight per floor area of the building
F_{OP}	Stiffness degradation factor as a function of opening area *(OP)* of the wall
OP	Opening area of the wall
n	Number of walls
γ	Unit weight
q_u	Unconfined compression strength
G_s	Specific gravity
SR	Slenderness ratio
F_{SR}	Strength reduction factor as a function of slenderness ratio
F_{AR}	Strength reduction factor based on aspect ratio
H_w	Height of the wall
L_w	Width of the wall
AR	Aspect ratio (H_w/L_w)
F_D	Weightage factor for deterioration
F_{VI}	Weightage factor for vertical irregularity
F_{HI}	Weightage factor for horizontal irregularity
F_T	Weightage factor for building age
F_P	Strength reduction factor for pounding effect
I_{RS}	Rapid seismic index
t_w	Average thickness of the wall
l	Length of the wall
l_x	Average length of the building in the x-direction
l_y	Average length of the building in the y-direction
τ_{wi}	Average shear strength of individual masonry wall
τ_0	Bed-joint shear strength
μ	Friction coefficient
f_{ae}	Gravity compressive stress applied to wall

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Abstract

The Rapid Seismic Assessment Method (RSAM) is an inexpensive and time-efficient method for assessing the seismic vulnerability of unreinforced masonry (URM) buildings to provide timely information for decision-making on the priority of buildings that need further seismic evaluation by vulnerability scoring. The simplicity of this method and the use of visual observations make it well-suited as a first-level assessment, thus helping to determine measures that will be taken and increasing the awareness of the public to the seismic hazard effects of URM buildings. To address the need for making vulnerable structures seismically resistant in seismically prone areas, this study focuses on URM buildings. This study investigates a systematic visual assessment method as a preliminary step towards the overall seismic evaluation of URM buildings. A rapid assessment approach has been developed, specifically tailored to the construction practices and materials of the buildings. This rapid assessment technique has been designed to assist in the development of a priority list for the separate determination of URM buildings that need additional detailed seismic analysis. Through the evaluation of the seismic capacity of each load-bearing masonry wall at different levels of a building, a rapid assessment index is developed. The technique developed in this study considers some of the critical factors that affect the seismic performance of masonry buildings, such as building type, number of stories, aspect ratio, slenderness ratio of walls, opening size, irregularities, pounding effect, construction age, and the physical condition of URM structures. To make the RSAM practical and valuable, available guidelines are used, and detailed seismic analysis is performed on several URM structures for comparison of the seismic index with the analytical and finite element models. The results from the studies show that this procedure can be used as an effective and practical means for the quick assessment of many masonry buildings located in seismically active areas. RSAM can be used to prioritize URM buildings that need further detailed seismic evaluation and to optimize the use of the limited available resources. This research not only demonstrates a practical solution for the initial seismic assessment of URM buildings but also highlights the necessity of implementing measures to protect vulnerable existing URM structures. It is crucial to take appropriate actions for the safety of the public from life-threatening situations in seismically and potentially active regions.

CHAPTER 1: INTRODUCTION

1.1 General

This introductory chapter explains why there is a need for suitable seismic risk assessment methods for unreinforced masonry structures, which are incredibly numerous in most of the world. These types of structures, which are generally located in the old parts of the cities, are highly susceptible to earthquakes because the material used to make them is brittle, and the lack of reinforcement greatly diminishes their ability to carry earthquake-induced stresses. The introduction then describes why this is important, increasing awareness of earthquake hazard and the potentially catastrophic consequences for lives, safety, economy, and infrastructure, and that a complete understanding of the seismic vulnerability of unreinforced masonry buildings is indispensable to formulate adequate disaster risk reduction strategies. The introduction highlights the challenges of traditional assessment approaches, which are time and labor-consuming, making them unsuitable for widespread use. It demands a quick and efficient technique of seismic evaluation that possesses the ability to quickly screen hundreds or even thousands of potentially high-risk structures and place them at the front for more detailed analysis and possible retrofitting. Such an approach would not only improve earthquake preparedness but also help direct resources more efficiently, with the most vulnerable structures receiving prompt attention. Furthermore, the introduction explains why it is essential to develop seismic evaluation methods that are responsive to the peculiarities of the local building stock and regional seismicity. It describes that unreinforced masonry buildings have a diversity of construction practices, material characteristics, and structural configurations that need to be considered in the formulation of an assessment methodology. By considering these differences, more realistic and location-specific methods can be obtained and used for better risk reduction and mitigation. The introduction sets the stage for the research that will be conducted later to fill the gaps in the past methodology and help in the development of safer and more resilient communities in earthquake-prone areas.

1.2 Background

The Unreinforced Masonry (URM) building is the most vulnerable building in this kind of environment. The URM building occupies multidirectional areas. Having a brittle design and low seismic load-carrying capacity, these structures are a major threat in an earthquake event. The seismic hazard of URM constructions in Dhaka is also increased by local factors, including high structural density, non-uniform construction practices, and possibly complex topographic effects that may enhance seismic forces. Despite all these clear-cut factors, the assessment methods widely used by practitioners, i.e., Rapid Visual Screening (RVS), do not properly account for these significant parameters and therefore normally result in insufficient seismic hazard analyses. Seismic vulnerability assessment is an essential element in assessing the potential hazard that buildings are exposed to during an earthquake. Several different methods have been developed for estimating the seismic vulnerability of buildings, ranging from simple visual inspection to thorough engineering analysis. Of these methods, Rapid Visual Screening (RVS) has received more attention because the method can be used to assess many buildings quickly. This literature review aims to present the development, application, and variations around the world of RVS and other techniques of vulnerability assessment, such as Simplified Vulnerability Assessment (SVA) and Detailed Vulnerability Assessment (DVA). The application of these techniques in various parts of the world, including the USA, Turkey, the Philippines, and several European countries, is also highlighted. An advanced world usually has a huge database of earthquake damage that gives clues about the possible structural vulnerability and mode of failure. These databases have helped us to improve the seismic evaluation methodologies over the years, and region-specific adjustments have been made with improved accuracy. On the other hand, Bangladesh lacks a substantial database, which poses a significant constraint when applying and calibrating methods such as RVS, SVA, and DVA. Given the absence of past data, the application of such methodologies cannot effectively capture the peculiar frailties of Bangladeshi structures, especially URM buildings. This limitation highlights the need to develop novel, localized test procedures with the potential to address the special problems posed by the local building methods, geology, and urbanization processes in Bangladesh. RVS procedures typically focus on generalized criteria and disregard site-specific vulnerabilities, such as spacing of buildings, where closely constructed buildings interact and suffer increased damage from earthquakes. Furthermore, structural details like overhangs, which introduce secondary stress concentrations, are rarely considered in traditional screen tests. The quality of construction, which is generally variable across Dhaka due to the absence of enforcement of building codes, further undermines the validity of traditional screening devices. Additionally, local topography, which can unexpectedly amplify seismic loads, is still largely unaddressed in traditional procedures. These exclusions give rise to significant knowledge gaps in interpreting the true seismic vulnerabilities of Dhaka's built environment, particularly for URM structures that, by nature, are brittle and prone to collapse under seismic loads. The Bangladesh Comprehensive Disaster Management Program (CDMP) recognized the need for effective seismic evaluation techniques to confirm the accuracy of the nation's high concentration of URM structures. CDMP maintains that approximately 30% of Dhaka city and its surrounding towns are URM buildings. The ratio highlights the uneven risk of earthquakes in the city and its surrounding districts. Outside Dhaka, the scenario at a national level also plays an important role, with URM buildings making up a huge majority of the structural part of urban as well as rural areas. Such buildings, in most cases, are not constructed according to seismic design codes, posing a significant hazard to Bangladesh, a seismically active region. The magnitude of the problem warrants the creation of assessment tools with the potential to detect and quantify the seismic risk induced by URM buildings regularly. To evade such limitations, the Rapid Seismic Assessment Method (RSAM) is a successful remedy to investigate the seismic vulnerability of URM buildings. RSAM monitors a greater range of measurable parameters, such as structural cracking, deformation, and displacement, to yield a better and more quantitative assessment of vulnerability. Still, while RSAM promises to overcome the limitations inherent in conventional methods, its use in URM structures remains to be explored to its optimum capacity. The distinct structural features of URM buildings, such as their masonry-based nature and vulnerability to cracking and brittle failure, present an issue that particularly trained assessment tools must address. The population density of Dhaka and the whole country in URM buildings, along with their susceptibility to earthquakes, underscores the urgent need for the development and improvement of more precise RSAM for this type of construction. This study caters to this imperative requirement by examining the practicability and proficiency of RSAM for seismic vulnerability assessment of URM buildings in Dhaka and Bangladesh as a whole. By adopting a systematic investigation of RSAM's capacity to identify site-specific vulnerabilities of URM buildings, the study aims to develop a more effective tool for determining vulnerable buildings and prioritizing appropriate retrofitting. These findings are crucial to the formulation of successful seismic risk reduction programs and the development of Bangladesh's urban and rural infrastructure to withstand earthquakes. It is timely that research is undertaken in this area because the rising seismic risk underpinned by burgeoning urbanization requires coherent and localized evaluation methods that can aid in sustainable development in the country.

1.3 Problem Statement

Although we've improved significantly in assessing how buildings withstand earthquakes, these methods are less effective in countries like Bangladesh. Dhaka, the capital, is growing super-fast and has all sorts of buildings, plus it's in an earthquake-prone zone. Figuring out how shaky things are there is tough for a bunch of linked reasons, which makes it hard to know the real risks. A significant issue is the lack of reliable information on past earthquakes. Like most growing cities, Dhaka lacks solid records on past earthquakes, building damage, or how buildings fared. Without that data, it's hard to know if our methods for assessing building stability are accurate. This makes our guesses uncertain. If we don't have the correct info, these guesses can be way off, either saying buildings are safer or riskier than they really are. Also, the way buildings are put together in Dhaka varies a lot. The materials, their usage, and adherence to rules all change due to financial constraints, inadequate supplies, and uneven enforcement of building regulations. This means buildings can be strong in some spots and weak in others, so the usual ways of checking don't always work. For example, two buildings that look the same might do totally different things in an earthquake because one was built better something that most tests miss. Differences in seismic practices and codes also create obstacles to the practical application of standardized seismic vulnerability assessment procedures in Dhaka. While developed countries have highly advanced and strictly implemented seismic codes guiding construction practices to ensure some level of earthquake resistance, Dhaka's seismic codes are less frequently enforced. This reduced regular enforcement means that structures in the city tend to be less resilient to seismic activity. Moreover, the techniques formulated for regions with strict seismic codes might not be fully applicable and efficient in the context of Dhaka, where such codes are typically nonexistent or weakly enforced. Additionally, existing seismic vulnerability evaluation techniques, such as Rapid Visual Screening (RVS), fail to address crucial factors that significantly contribute to the seismic vulnerability of buildings in Dhaka. These include the construction of proximity, where adjoining buildings can increase the damage during an earthquake as they interact; overhangs, which introduce additional points of stress into a building's structure; overall construction quality, which varies wildly across the city; and topographic effects, where the local terrain can increase the seismic forces in varying and unpredictable ways. The omission of these factors from most assessment techniques can leave a distorted and possibly misleading impression of the actual seismic vulnerability of a building, especially under the diverse and often challenging conditions of Dhaka. Due to these problems, the Rapid Seismic Assessment Method (RSAM) has emerged as a viable option for rapidly assessing reinforced concrete buildings in Dhaka. RSAM is better than other methods because it considers more factors, such as cracks, bends, and shifts in building parts. These things give a clearer idea of how likely a building is to be damaged by an earthquake, which could help decide which buildings to check and fix first. Although RSAM has potential, it remains underdeveloped and underutilized, particularly for Unreinforced Masonry (URM) buildings in Dhaka. There are many URM buildings in the city, made of brick, not reinforced with concrete or steel, and they are very likely to be damaged in earthquakes. URM buildings tend to crack and fall apart, making them hard to check using standard methods. RSAM, which looks at visual signs of structural health, might be a better way to check these buildings quickly. Still, we need to do more work to finish RSAM, test it out in different places, and make sure it can spot the weaknesses of URM buildings in earthquake-prone places like Dhaka. This research aims to address these issues by examining whether RSAM can be a valuable method for assessing the likelihood of damage to buildings in Dhaka, particularly URM buildings, in an earthquake. By understanding how well RSAM works and where it has limits, this research aims to help create good plans to lower earthquake risks and make Dhaka's buildings stronger.

1.4 Objectives of the Study

This study focuses on reviewing and developing a rapid seismic assessment tool targeting vulnerable existing URM buildings without a damage database. The key objectives of this thesis are:

a) To review the existing global rapid visual screening (RVS) methods for unreinforced masonry buildings to find the limitations of those methods from the perspective of Bangladesh.
b) To develop a Rapid Seismic Assessment Method (RSAM) for the assessment of existing URM buildings in Bangladesh.

The primary objective is to conduct a comprehensive review of existing RVS techniques employed worldwide to assess the seismic vulnerability of URM buildings. The study will critically evaluate these methods, establishing their merits and shortcomings, particularly when applied to the structural and environmental conditions prevalent in Bangladesh. The criticism will identify the shortfalls through which international techniques may be deficient in addressing the specific challenges posed by the construction activities of cities, the quality of materials, and the density of cities like Dhaka. By identifying these weaknesses, this study seeks to lay the groundwork for developing a more tailored assessment technique that can accurately quantify the seismic hazards posed by URM structures in Bangladesh. From the outcome of the first objective, this study aims to design and suggest an RSAM particularly for Dhaka's URM buildings. This creation will consider Dhaka's unique architectural styles, construction materials, and local seismic hazards. The envisioned RSAM shall incorporate parameters often overlooked in global RVS practices but are of great relevance in Dhaka, for instance, variation of building quality, building proximity, overhangs, and topographical influence. The methodology will be developed to provide a more realistic and practical tool for city planners, engineers, and disaster management officials to prioritize structures for seismic detailed inspections and retrofitting. Additionally, the development process will utilize field testing and validation to ensure the RSAM's performance and reliability in quantifying the seismic vulnerability of Dhaka's stock of URM buildings. From this tailored method, the study aims to contribute towards enhancing the seismic resilience of Dhaka's urban environment.

1.5 Scope of the Study

This research aims to investigate methods for rapidly assessing the safety of old brick buildings during earthquakes, with a focus on Dhaka, Bangladesh. The goal is to create a simple way to spot the most at-risk buildings. First, this study will examine how other countries inspect similar buildings. This study aims to investigate the effectiveness of these methods in Dhaka, a city with unique building construction practices and high population density. The study will consider factors such as the proximity of buildings, the impact of the ground, and the construction methods used, which can vary from place to place. Next, based on the findings, this study will develop a simple test, called RSAM, to assess brick buildings in Dhaka. This test will consider the unique aspects of Dhaka, such as the construction methods and materials used in its buildings. After creating the RSAM test, this study will apply it to real buildings in Dhaka to assess its effectiveness. This study aims to evaluate the test's usability and its capacity to identify buildings in need of the most help accurately. The aim is to make a test that city planners and engineers can use to keep Dhaka safe from earthquakes.

1.6 Methodology

The initial step in the process is to conduct a strict visual inspection of the entire building to assess its structural adequacy. This inspection is comprehensive, with the inspector carefully inspecting all observable features of the structure, including significant features like the walls, roof, foundation, support columns, beams, and other load-bearing structures. This inspection seeks to detect any deterioration, harm, or issues like cracks, spalling, deformation, water stains, or other signs that could risk the building's stability or resistance to earthquakes. The type and size of harm, such as small cracks versus wide fissures, and whether the harm seems limited to some spots or widespread, can show the cause of structural problems. Besides looking at the building's current physical state, the inspector considers the history and context that could impact its longevity. This includes the building's age, which can show wear over time, and the original building materials and methods. Older buildings may use old design rules or materials that are weak against earthquakes, making them more susceptible to damage. The inspector checks if there has been any work done to improve, fix, or update the building since it was built. Notes on the quality, quantity, and type of changes made, as they significantly impact the building's current strength and its ability to withstand earthquake forces. The inspection also examines the building's location and the surrounding environment. Soil types, closeness to fault lines, and past earthquakes in the area are all considered because they contribute to the overall earthquake risk. For instance, buildings on unstable or liquefiable soils are more likely to be severely damaged by an earthquake because the ground they're on isn't firm. Buildings in areas with many past earthquakes may already show signs of stress. The structural layout, including the placement of walls and openings, the presence of unusual features such as soft stories, and the distribution of weight, is also examined to determine how the building will behave during an earthquake. All these things help form a full view of the building's structural health, which is key for guiding what to do next to judge earthquake risk and make plans to lower it. The method used can give the results below: analysis of existing RVS and VIM methodologies and their applicability in different contexts.

a) Development of a rapid assessment approach tailored to the specific construction materials and practices associated with URM buildings.
b) Establishing a priority list for identifying URM buildings that require in-depth seismic assessments.
c) Evaluation of the seismic capacity of load-bearing masonry walls at different building levels.
d) Consideration of various critical factors such as building type, number of stories, aspect ratio, slenderness ratio of walls, opening dimensions, irregularities, pounding effect, construction age, and physical condition of URM buildings.
e) Validation of the RSAM approach through comparison with existing guidelines and detailed seismic evaluations.

1.7 Research Flow Diagram

RSAM is implemented through a two-step process. The first step involves preparing a detailed survey datasheet to record all relevant data collected during the inspection systematically. The second process is the rating of the building as per the RSAM criteria and is illustrated graphically in the flow diagram in Figure 1.1. This method allows for a detailed examination and rating of all key aspects related to a building's vulnerability to seismic activity.

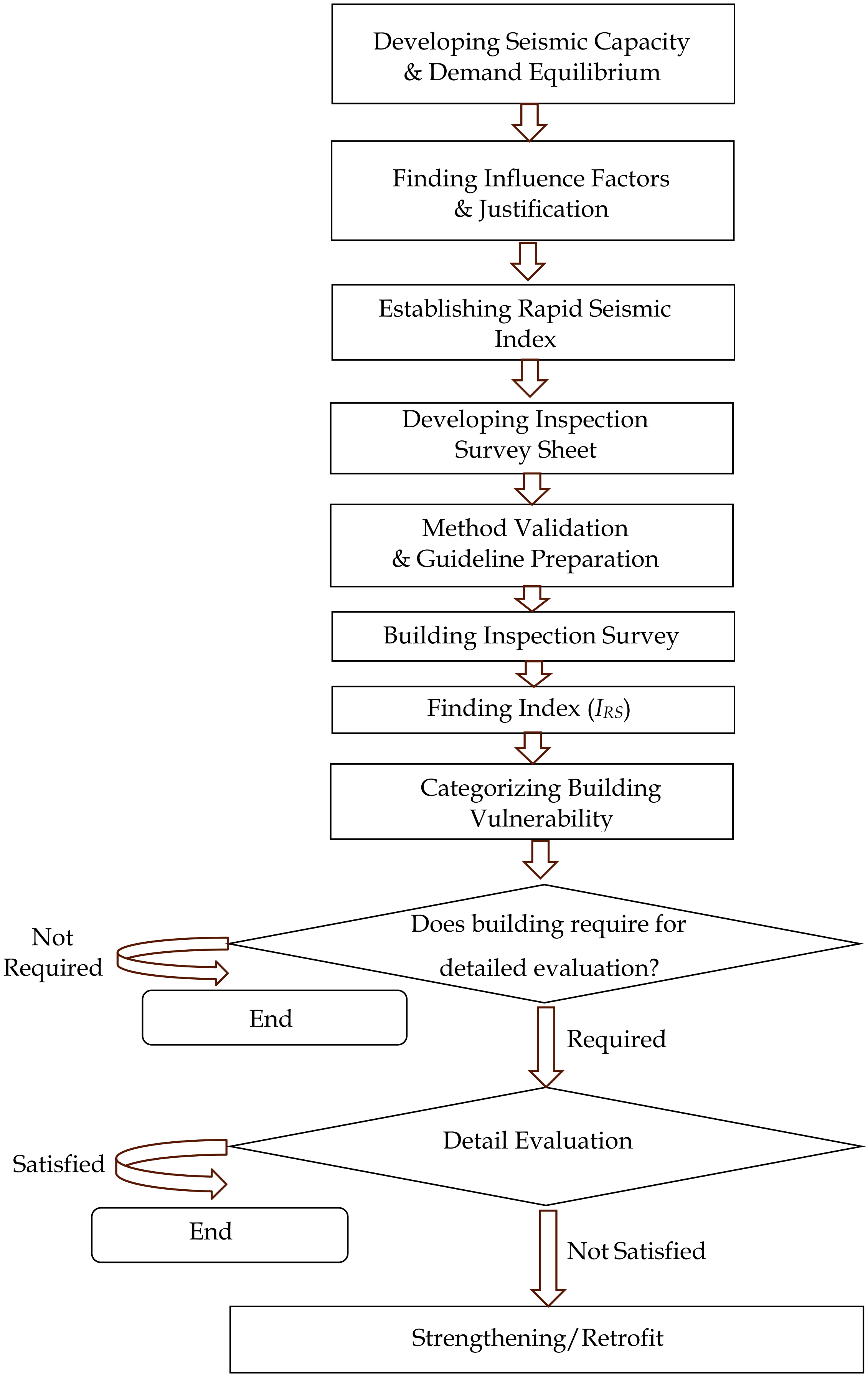


Fig. 1.1 General flow diagram for the development and application of the Rapid Seismic Assessment Method for URM buildings.

1.8 Organization of the Thesis

This systematic process makes sure that every key aspect of a building's seismic vulnerability is carefully checked and rated. This paper is arranged in the following way:

Chapter 1: Introduction

- This section provides the background, states the problem, lists the goals, defines the scope, and outlines the study's setup.

Chapter 2: Literature Review

- Examines current studies and methods for assessing the seismic state of URM buildings. It points out what's missing and helps create a quick way to assess buildings.

Chapter 3: Development of Rapid Seismic Assessment Method (RSAM)

- Provides an in-depth look at making the RSAM, including the RS approach and key considerations for assessment.

Chapter 4: Method Adequacy and Priority Setting

- Evaluates the effectiveness of the RSAM, discusses its contributions, and guides future studies and guidelines. It gives a close seismic check of some unreinforced masonry (URM) buildings to prove the RSAM works.

Chapter 5: Application of Rapid Seismic Assessment Method (RSAM)

- Shows how to use the RSAM in real situations, focusing on why it matters and the impact it has.

Chapter 6: Conclusions and Recommendations

- This summary encapsulates the study's findings, highlights the RSAM's contributions, and offers suggestions for future studies and the implementation of rules.

CHAPTER 2: LITERATURE REVIEW

2.1 General

This section reviews existing studies about quickly checking methods for unreinforced brick buildings before or after earthquakes. First, it provides a basic overview of how these assessment methods originated and evolved. Then, it talks about past earthquakes in Bangladesh, explaining the area's geological structure and pointing out active fault lines in and around the country, using records of past earthquakes. The primary focus is on Dhaka, the capital of Bangladesh, due to its large population and numerous brick buildings. The review then discusses why brick buildings in Dhaka are susceptible to damage from earthquakes, primarily due to poor building methods and structural issues. Lastly, the section goes over ways to measure earthquake risks, which is essential for creating better and faster assessment methods that fit the local situation.

2.2 History of Rapid Assessment Methods

In areas prone to earthquakes, it's crucial to assess how unreinforced buildings can withstand shaking. This is key to managing disasters. It's especially true in crowded cities where many people could get hurt and property could be damaged. Over time, people worldwide have developed various methods to assess buildings' earthquake resistance. Back in the late 1980s, the Applied Technology Council (ATC) came up with Rapid Visual Screening (RVS) to quickly check buildings for earthquake weakness (ATC, 1989). Several established standards are found in the Federal Emergency Management Agency (FEMA) for seismic risk assessment and building rehabilitation. These are FEMA 178 (1992), FEMA 310 (1998), and FEMA 154 for RVS of buildings, initially published as FEMA 154 (1988) and revised in 2002. FEMA 154 (2002), for instance, involves the determination of an underlying structural score based on the building's lateral force-resisting system, with performance modifiers to account for number of stories, plan and vertical irregularities, pre-code or post-benchmark code detailing, and soil type, as detailed in FEMA 155 (2002), which was initially published earlier as FEMA 155 (1988). Again, experts like Rai (2005) have looked at these ways. Usually, there's a simple process. It starts with a quick look around (Tier 1), then a more detailed check (Tier 2), and ends with an intense dive (Tier 3). In FEMA's Tier 1 screening phase (FEMA 310, 1998), there are appraisal statements for each building type to be employed to determine the performance level of the building. The quick look around (RVS) is cheap and easy. It helps sort buildings to identify those that need a closer look first. RVS means walking around to visit buildings. Nowadays, it's getting help from computer programs (GIS) to make it faster and more exact. The methods followed under RVS tend to be formulated from the configuration factors of seismic vulnerability and propose a scoring system as the foundation for dividing buildings into different risk groups (Jain et al. 2010). However, the usage of the seismic evaluation guidelines in developing countries has been a subject of critique. Researchers such as D'Ayala and Charleson (2002) have argued critically regarding the relevance of such guidelines, particularly in contexts where economic, structural, and regulatory conditions tend to differ significantly from the developed world. This phase imposes a significant pre-code penalty on buildings designed and constructed before seismic codes were enforceable, and a post-benchmark positive characteristic for buildings built after significant code improvements. The pre-code and post-benchmark modifiers exert substantial power relative to the structural score. FEMA classifies four- to seven-story buildings and those with seven or more stories as separate categories, awarding the latter a greater score. In addition, FEMA classifies both plan irregularities and vertical irregularities, but with higher modifiers for vertical irregularities (e.g., soft stories), as they are more vulnerable than plan irregularities that sidewalk surveys can easily identify.

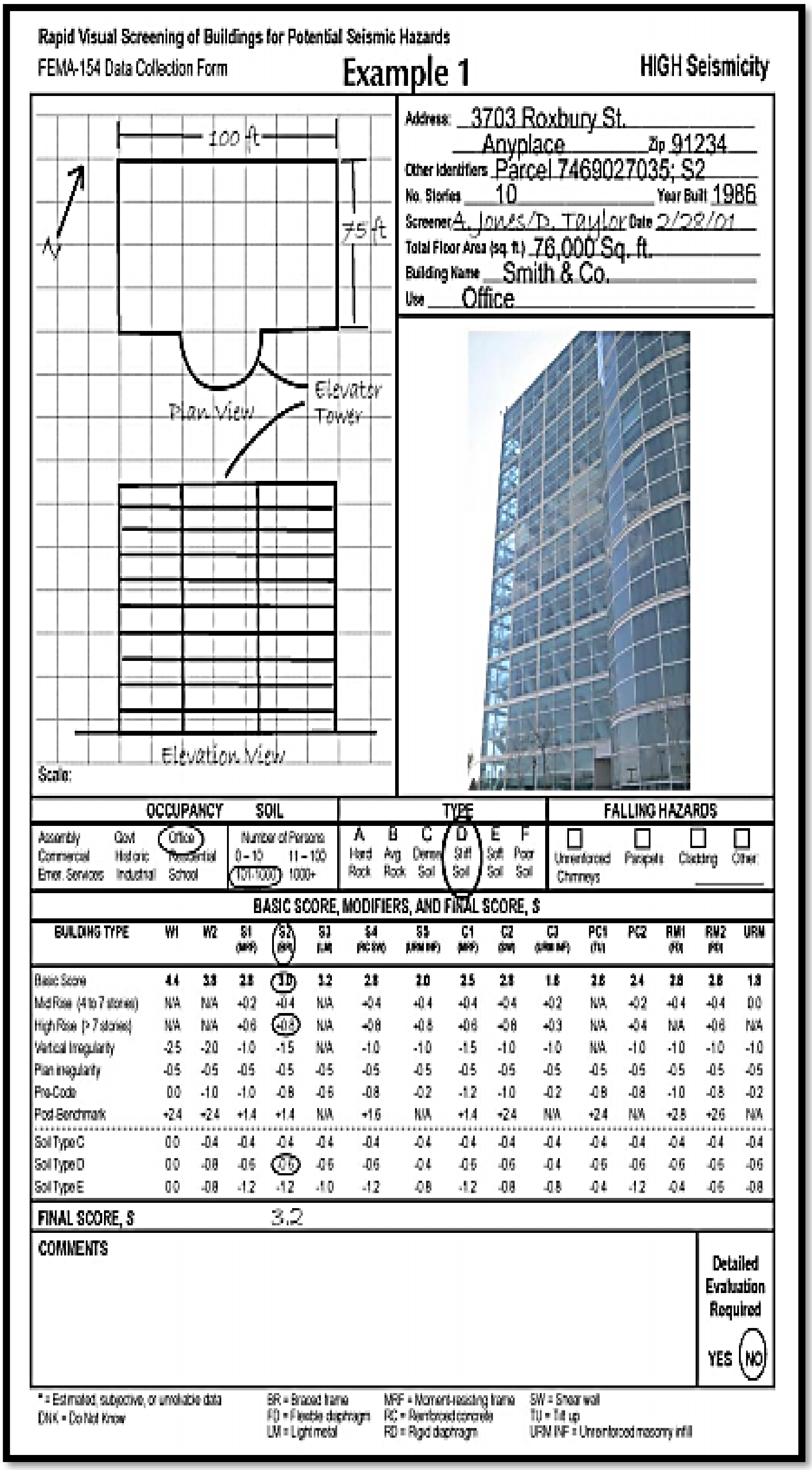
2.3 Detailed Procedures of Popular Existing Methods

Seismic vulnerability analysis is a critical activity in identifying the risk caused by buildings in the event of an earthquake. Various methods have been developed to evaluate the seismic vulnerability of buildings, ranging from a basic visual inspection to sophisticated engineering analysis. Among these methods, Rapid Visual Screening (RVS) has gained immense popularity as it can efficiently evaluate large numbers of buildings within a short time. This literature review assesses the history, application, and global applications of RVS as well as allied methods of vulnerability analysis, such as Simplified Vulnerability Assessment (SVA) and Detailed Vulnerability Assessment (DVA). The review also examines the global application of these methods, including in countries such as Bangladesh, Turkey, the Philippines, and various European nations.

2.3.1 Rapid Visual Screening (RVS)

Basically, someone who knows what to look for walks around the building, checking for obvious weak spots, such as its unusual shape, height, material, and age (ATC, 1989). The person then gives the building a score based on their observations, which shows how likely it is to get damaged in an earthquake.

- ATC-21 and FEMA 154: The ATC-21 project systemized the RVS, and in 1988, FEMA 154 came out. In Figure 2.1, FEMA 154 provided guidelines that became the standard for assessing earthquake safety in buildings in the United States and around the world (FEMA, 1988/2002).



Rapid Visual Screening of Buildings for Potential Seismic Hazards

FEMA-154 Data Collection Form

Example 1

HIGH Seismicity

Address: 3703 Roxbury St.
Anyplace Zip 91234
Other Identifiers Parcel 7469027035; S2
No. Stories 10 Year Built 1986
Screener A. Jones/D. Taylor Date 2/28/01
Total Floor Area (sq. ft.) 76,000 Sq. ft.
Building Name Smith & Co.
Use Office

Scale:

OCCUPANCY

Assembly, Govt, [✓ Office], Commercial, Historic, Residential, Emer. Services, Industrial, School

Number of Persons: 0 – 10, 11 – 100, [✓ 101-1000], 1000+

SOIL / **TYPE**

A Hard Rock, B Avg Rock, C Dense Soil, [✓ D Stiff Soil], E Soft Soil, F Poor Soil

FALLING HAZARDS

☐ Unreinforced Chimneys ☐ Parapets ☐ Cladding ☐ Other: ______

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	[✓ S2 (BR)]	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	4.4	3.8	2.8	[✓ 3.0]	3.2	2.8	2.0	2.5	2.8	1.6	2.6	2.4	2.8	2.8	1.8
Mid Rise (4 to 7 stories)	N/A	N/A	+0.2	+0.4	N/A	+0.4	+0.4	+0.4	+0.4	+0.2	N/A	+0.2	+0.4	+0.4	0.0
High Rise (> 7 stories)	N/A	N/A	+0.6	[✓ +0.8]	N/A	+0.8	+0.8	+0.6	+0.8	+0.3	N/A	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-2.5	-2.0	-1.0	-1.5	N/A	-1.0	-1.0	-1.5	-1.0	-1.0	N/A	-1.0	-1.0	-1.0	-1.0
Plan irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-1.0	-1.0	-0.8	-0.6	-0.8	-0.2	-1.2	-1.0	-0.2	-0.8	-0.8	-1.0	-0.8	-0.2
Post Benchmark	+2.4	+2.4	+1.4	+1.4	N/A	+1.6	N/A	+1.4	+2.4	N/A	+2.4	N/A	+2.8	+2.6	N/A
Soil Type C	0.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Soil Type D	0.0	-0.8	-0.6	[✓ -0.6]	-0.6	-0.6	-0.4	-0.6	-0.6	-0.4	-0.6	-0.6	-0.6	-0.6	-0.6
Soil Type E	0.0	-0.8	-1.2	-1.2	-1.0	-1.2	-0.8	-1.2	-0.8	-0.8	-0.4	-1.2	-0.4	-0.6	-0.8

FINAL SCORE, S 3.2

COMMENTS

Detailed Evaluation Required

YES [✓ NO]

* = Estimated, subjective, or unreliable data
DNK = Do Not Know
BR = Braced frame
FD = Flexible diaphragm
LM = Light metal
MRF = Moment-resisting frame
RC = Reinforced concrete
RD = Rigid diaphragm
SW = Shear wall
TU = Tilt up
URM INF = Unreinforced masonry infill

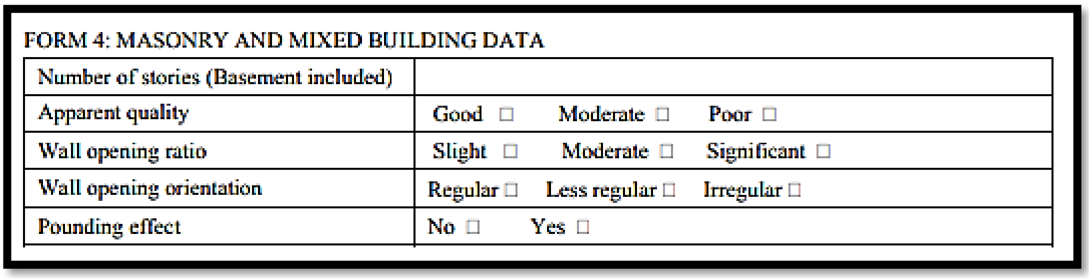
Fig. 2.1 FEMA 154 data collection and assessment form.

- Advantage of RVS: RVS is excellent because it's quick and inexpensive. You can use it to quickly screen lots of buildings and identify which ones need more attention (FEMA, 1988/2002).

2.3.2 RVS in Global Context

RVS is used all over the place because different countries have different earthquake situations and building practices. Below are some examples of RVS utilization in various countries:

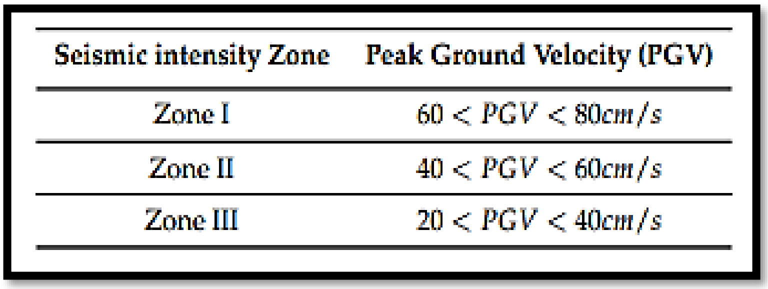
- Earthquake Master Plan for Istanbul (EMPI) (2003), Turkey: The RVS method was a significant component of the Earthquake Master Plan for Istanbul (EMPI), built for establishing the seismic vulnerability of buildings in one of the world's most seismically active cities. The method was adapted based on the local building types and seismicity; the step-by-step process is depicted from Figure 2.2 to Figure 2.5, such that the evaluation is applicable and accurate to the respective zones (Yucemen, 2003).



FORM 4: MASONRY AND MIXED BUILDING DATA

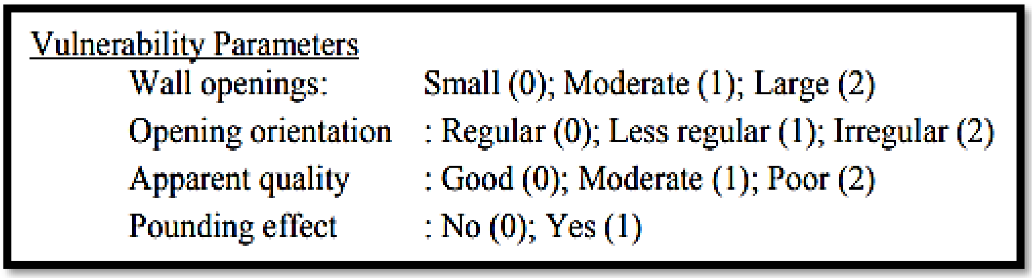
Number of stories (Basement included)	
Apparent quality	Good ☐ Moderate ☐ Poor ☐
Wall opening ratio	Slight ☐ Moderate ☐ Significant ☐
Wall opening orientation	Regular ☐ Less regular ☐ Irregular ☐
Pounding effect	No ☐ Yes ☐

Fig. 2.2 URM and mixed building data (EMPI, 2003).



Seismic intensity Zone	Peak Ground Velocity (PGV)
Zone I	$60 < PGV < 80cm/s$
Zone II	$40 < PGV < 60cm/s$
Zone III	$20 < PGV < 40cm/s$

Fig. 2.3 Seismic zoning and PGV ranges (EMPI, 2003).



Vulnerability Parameters

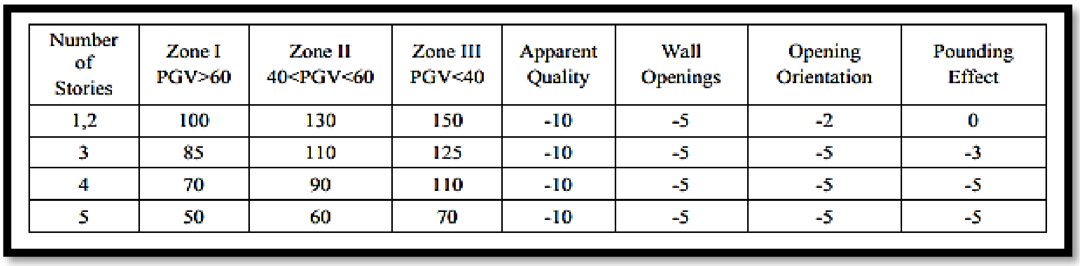
Wall openings: Small (0); Moderate (1); Large (2)

Opening orientation : Regular (0); Less regular (1); Irregular (2)

Apparent quality : Good (0); Moderate (1); Poor (2)

Pounding effect : No (0); Yes (1)

Fig. 2.4 Vulnerability parameters (EMPI, 2003).



Number of Stories	Zone I PGV>60	Zone II 40<PGV<60	Zone III PGV<40	Apparent Quality	Wall Openings	Opening Orientation	Pounding Effect
1,2	100	130	150	-10	-5	-2	0
3	85	110	125	-10	-5	-5	-3
4	70	90	110	-10	-5	-5	-5
5	50	60	70	-10	-5	-5	-5

Fig. 2.5 Vulnerability scores for URM buildings (EMPI, 2003).

- **Austria/Vienna/Portugal/Italy RVS Practice**: Other European countries, such as Austria, Vienna, Italy, and Portugal, have also implemented RVS procedures, particularly after the catastrophic earthquakes at L'Aquila in 2009 and Emilia-Romagna in 2012. The European implementation of RVS includes factors concerning aging, older, and historic structures, common among these nations (Cosenza et al., 2012).

- **City of Manila, Philippines Practice**: In the Philippines, the City of Manila used the ATC-21 (FEMA-P154) RVS method to assess building earthquake vulnerability. This was necessary for a city based in a highly seismic area, where it needs to identify risks to prevent them rapidly (FEMA, 2015).

2.3.3 Simplified Vulnerability Assessment (SVA)

RVS is now used all over the world, but countries have different earthquake situations and construction methods. Simplified Vulnerability Assessment (SVA) examines vulnerabilities more closely than RVS. But it still depends on looking at buildings and doing a bit of math. Usually, SVA involves checking building plans, measuring the structure, and doing simple math to estimate how a building might handle an earthquake.

- Analysis: Unlike RVS, SVA uses a mathematical procedure. This could involve checking if the building follows earthquake safety rules, examining how loads move through the structure, and verifying whether good materials were used during construction.
- How it's Used: SVA is most effective on buildings identified by RVS as potentially having issues. It helps figure out how risky they really are. It's a mix between a glance and a thorough check-up. It gives a better idea of what's going on without costing too much.

2.3.4 SVA in Seismic Planning

Using simplified vulnerability assessment in seismic design helps better check how buildings might fail. Quick looks can team up with a bit of math to spot buildings that seem okay by quick visual screening but could still get damaged in an earthquake (Cosenza et al., 2012).

- Benefits: Simplified vulnerability assessment is quick and not too hard, making it ideal when you have a limited budget or time for checking. You can also use it to check essential spots such as schools, hospitals, and government offices (Cosenza et al., 2012).

2.3.5 Detailed Vulnerability Assessment (DVA)

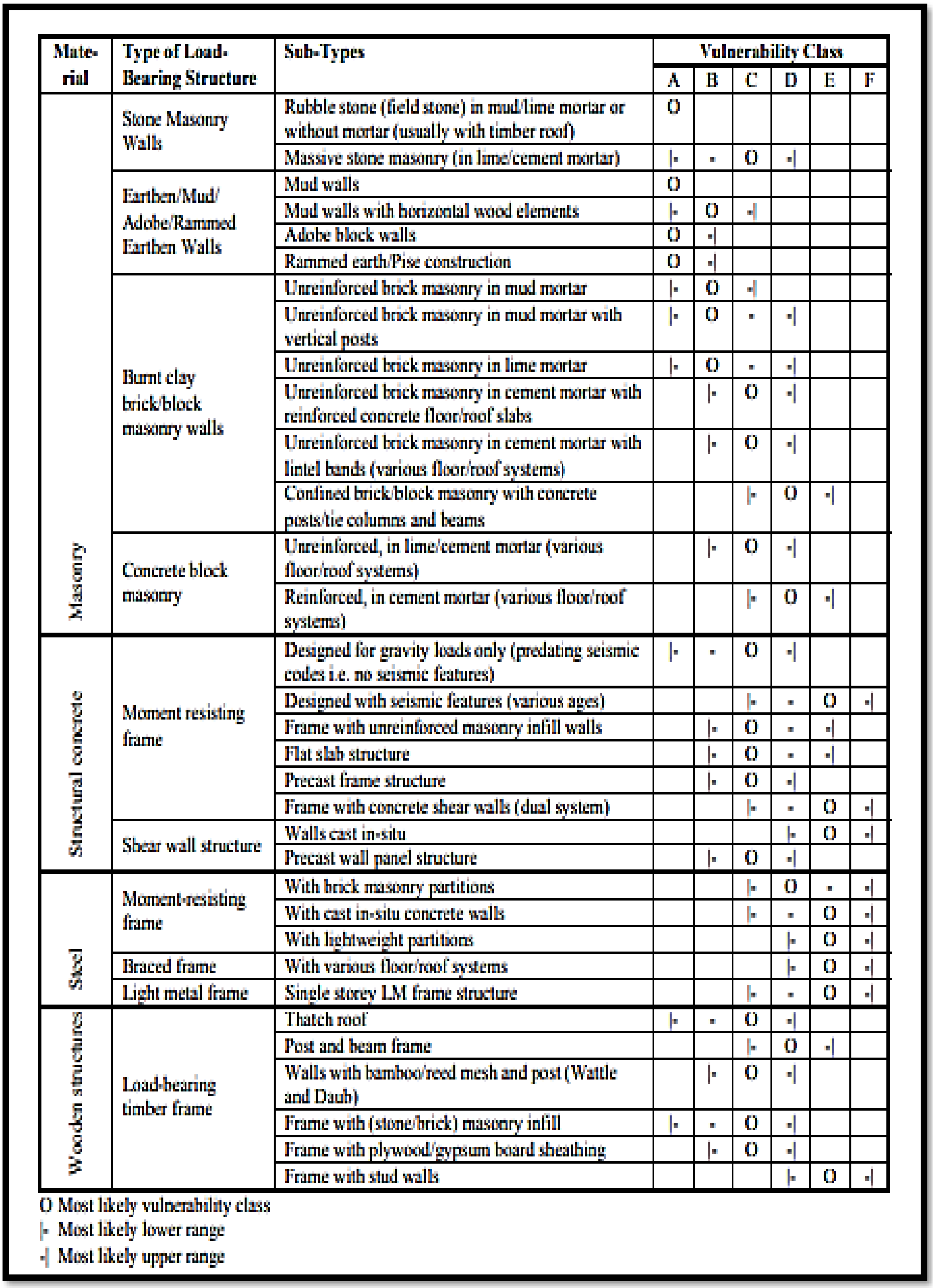
A Detailed Vulnerability Assessment (DVA) is essentially the ultimate way to identify a building's resilience to an earthquake. It uses detailed simulations and analysis, incorporating factors such as the building's materials, shape, and its movement during ground shaking (Nanda & Majhi, 2013).

- Computer Analysis: DVA uses fancy computer programs to mimic how a building reacts when the Earth moves. This method can predict with reasonable accuracy what will happen to a building during a seismic event, figuring out where it might crack or collapse (Nanda & Majhi, 2013).
- How It's Used: DVA is usually for buildings that are important or seem shaky after a quick check. It's also beneficial when constructing new buildings to make them as earthquake resilient as possible (Cosenza et al., 2012).

2.3.6 Role of DVA in Earthquake Preparedness

DVA is essential for getting ready for earthquakes. It provides simple data on how buildings should withstand a quake (Cosenza et al., 2012). This info helps people decide if they should fix up, strengthen, or tear down buildings that might not be safe in an earthquake (Cosenza et al., 2012).

- Fixing and Strengthening: DVA can spot weak points in a building's design or how it was built. Fixing these spots makes the building stronger against earthquakes. This means fixes can be done more efficiently, saving time and money (Nanda & Majhi, 2013), as illustrated in Figures 2.6 and 2.7.



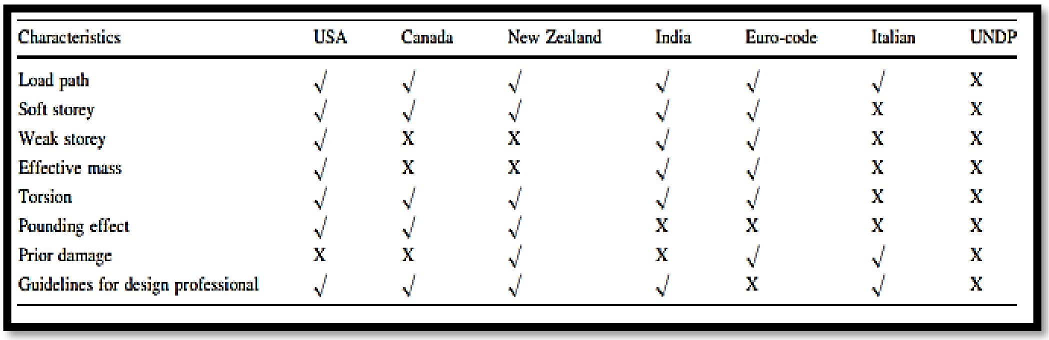
Material	Type of Load-Bearing Structure	Sub-Types	Vulnerability Class					
			A	B	C	D	E	F
Masonry	Stone Masonry Walls	Rubble stone (field stone) in mud/lime mortar or without mortar (usually with timber roof)	O					
		Massive stone masonry (in lime/cement mortar)	|•	•	O	•|		
	Earthen/Mud/ Adobe/Rammed Earthen Walls	Mud walls	O					
		Mud walls with horizontal wood elements	|•	O	•|			
		Adobe block walls	O	•|				
		Rammed earth/Pise construction	O	•|				
	Burnt clay brick/block masonry walls	Unreinforced brick masonry in mud mortar	|•	O	•|			
		Unreinforced brick masonry in mud mortar with vertical posts	|•	O	•	•|		
		Unreinforced brick masonry in lime mortar	|•	O	•	•|		
		Unreinforced brick masonry in cement mortar with reinforced concrete floor/roof slabs		|•	O	•|		
		Unreinforced brick masonry in cement mortar with lintel bands (various floor/roof systems)		|•	O	•|		
		Confined brick/block masonry with concrete posts/tie columns and beams			|•	O	•|	
	Concrete block masonry	Unreinforced, in lime/cement mortar (various floor/roof systems)		|•	O	•|		
		Reinforced, in cement mortar (various floor/roof systems)			|•	O	•|	
Structural concrete	Moment resisting frame	Designed for gravity loads only (predating seismic codes i.e. no seismic features)	|•	•	O	•|		
		Designed with seismic features (various ages)			|•	•	O	•|
		Frame with unreinforced masonry infill walls		|•	O	•	•|	
		Flat slab structure		|•	O	•	•|	
		Precast frame structure		|•	O	•|		
		Frame with concrete shear walls (dual system)			|•	•	O	•|
	Shear wall structure	Walls cast in-situ				|•	O	•|
		Precast wall panel structure		|•	O	•|		
Steel	Moment-resisting frame	With brick masonry partitions			|•	O	•	•|
		With cast in-situ concrete walls			|•	•	O	•|
		With lightweight partitions				|•	O	•|
	Braced frame	With various floor/roof systems				|•	O	•|
	Light metal frame	Single storey LM frame structure			|•	•	O	•|
Wooden structures	Load-bearing timber frame	Thatch roof	|•	•	O	•|		
		Post and beam frame			|•	O	•|	
		Walls with bamboo/reed mesh and post (Wattle and Daub)		|•	O	•|		
		Frame with (stone/brick) masonry infill	|•	•	O	•|		
		Frame with plywood/gypsum board sheathing		|•	O	•|		
		Frame with stud walls				|•	O	•|

O Most likely vulnerability class

|• Most likely lower range

•| Most likely upper range

Fig. 2.6 Vulnerability classes (Nanda & Majhi, 2013).



Characteristics	USA	Canada	New Zealand	India	Euro-code	Italian	UNDP
Load path	√	√	√	√	√	√	X
Soft storey	√	√	√	√	√	X	X
Weak storey	√	X	X	√	√	X	X
Effective mass	√	X	X	√	√	X	X
Torsion	√	√	√	√	√	X	X
Pounding effect	√	√	√	X	X	X	X
Prior damage	X	X	√	X	√	√	X
Guidelines for design professional	√	√	√	√	X	√	X

Fig. 2.7 Different RVS methods' characteristics (Nanda & Majhi, 2013).

- Policy Implications: DVA's outcome can help update building rules, making sure new buildings can handle earthquakes. Plus, it provides valuable information for planning disaster responses, which can mitigate the impact of earthquakes on people (Cosenza et al., 2012).

2.3.7 Comparative Analysis of RVS, SVA, and DVA

Primarily, there are three ways to check how strong a building is against earthquakes: RVS, SVA, and DVA. They all have both good and bad aspects. RVS is fast and cost-effective, but it lacks some detail. SVA is more accurate, but you need some engineers to help. DVA is the most thorough, but it requires a significant investment of time and money. Which one you pick depends on what you need. Use RVS if you have multiple buildings to inspect quickly. SVA is suitable for essential buildings or those that might be weak. DVA is best if a building is risky or needs a thorough inspection. You could even use all three in a plan. Begin with RVS for a quick overview, then use SVA to examine the weaker buildings more closely. Finish with DVA for the most important ones to plan fixes. These methods for checking buildings, RVS, SVA, and DVA, are all helpful in assessing how buildings will perform in an earthquake. Each one is good for different situations, depending on your budget and time constraints. RVS is widely used around the world because it's effective at inspecting numerous buildings, especially in areas prone to earthquakes. SVA strikes a good balance between quick and detailed, making it a good middle ground. DVA costs the most, but it provides the most insight into how a building will perform in an earthquake. It's particularly necessary for high-risk or essential buildings. In places like Bangladesh, where resources are scarce, using RVS has significantly helped determine which buildings to prioritize and how to prepare for earthquakes. International applications from these approaches in Turkey, the Philippines, and European countries highlight their adaptability and sensitivity to diverse seismic conditions. By integrating RVS, SVA, and DVA in a single seismic risk management strategy, communities can successfully become earthquake-resilient, ultimately reducing the risk of fatalities and property damage.

2.4 Earthquake History in Bangladesh

Bangladesh, being located at the confluence of the Indian, Eurasian, and Burmese tectonic plates, is a seismically active region. The tectonic complexities of the region, shaped by the ongoing collision between the plates, have formed a history of moderate to great earthquakes that have impacted the region over the past five centuries. It is necessary to know the seismic history of Bangladesh not merely to identify zones of risk but also to design and construct earthquake-resistant buildings to minimize the disastrous effects of potential future events. The recorded earthquake history of Bangladesh dates to the early 16th century. One of the most significant events (Hossain, 1989) in the region occurred in 1548 and was felt in the Bengal Basin, i.e., the southeastern part of the country. This earthquake was associated with the Indo-Burmese subduction zone, a major tectonic feature along the southeastern edge of Bangladesh (Sikder & Alam, 2003). The size of this event is not known, but it is one of the earliest significant seismic events in history. Human casualties and financial losses from this early event are not well documented, but its occurrence spurred seismic risk awareness in the area. A great earthquake struck this region in 1762, and its epicenter was in Bangladesh's eastern parts. This earthquake caused widespread destruction in the city of Dhaka and other cities of the Ganges-Brahmaputra Delta. This quake, with an estimated magnitude of approximately 7.5, caused immense destruction to buildings, and its effects were felt throughout the surrounding regions, including West Bengal in India. Historical documents show that the earthquake caused (Hoque & Khan, 2001) the collapse of several buildings in Dhaka, which was a city that had not been built with modern earthquake-resistant technologies (Islam et al., 2015). The earthquake caused many casualties, with estimates showing that thousands of individuals perished, while the economic effect was great due to the destruction of infrastructure and livelihood. A second great seismic event occurred in 1812, when a strong earthquake was felt in the northern part of Bangladesh. While not as far-reaching in its impact as the 1762 event, this earthquake was a sobering reminder of the seismic threat posed by the complex tectonic setting of the region. The earthquake was felt in large areas of Bangladesh, most prominently in the Rajshahi and Bogura regions. This event, and the aftershocks that followed it, heightened the awareness of seismic risk in the region, even though experience in earthquake-resistant design practice was not widespread at this time (Saha, 2015). The earthquake caused a few casualties and some damage to structures, though economic losses were less than those of previous major events. The most severe earthquake in the history of Bangladesh occurred on 12 June 1897, when the Great Assam Earthquake happened. The earthquake that struck the northeastern part of the Indian subcontinent, including parts of Bangladesh, was one of the most powerful ever to be felt in the region, with a magnitude of 8.1. The earthquake caused widespread damage in Dhaka and other major cities, and it left an indelible mark on the landscape, with large-scale ground shaking, surface ruptures, and landslides affecting the region. The 1897 earthquake was particularly devastating because it occurred in an area that had not been considered likely to produce such a large seismic event, highlighting the unpredictability of earthquakes in this region (Bilham & England, 2001). The earthquake caused the death of over 1,000 people, and the economic losses were heavy, with the large-scale destruction of buildings, roads, and arable lands. The financial losses were considerable, particularly due to the destruction of urban infrastructure, which interfered with trade and economic activity for years to come. The 20th century saw further seismic activity in Bangladesh, with some major earthquakes. One such incident occurred in 1943, when the region felt a strong earthquake. While it did not cause widespread destruction, it contributed to the growing fear of earthquake risk in the region. In 1960, another strong earthquake, though of smaller intensity, was felt in

Dhaka and surrounding areas, once again placing focus on the need for disaster preparedness (Kamal, 2013). A 6.6 Richter scale earthquake struck the Bangladesh-India border in 1997, causing widespread panic but relatively little damage due to the site and depth of the earthquake. The event served to underline Bangladesh's continued seismic risk, particularly in the northern and northeast parts of the country. The event caused numerous injuries but no appreciable loss of life. However, the economic impact was still considerable, with damage to businesses and infrastructure in the area. Seismic activity in Bangladesh has remained a concern in the 21st century, with small to moderate earthquakes being felt regularly, particularly at the northeastern and southeastern borders of the country. However, despite the frequency of such occurrences, Bangladesh has yet to experience another earthquake of the scale of the previous ones, such as the 1897 Assam earthquake. Despite this, the region's tectonic setting, along with unchecked urbanization and construction practices that typically ignore seismic safety, continues to place Bangladesh highly at risk of seismic activity in the future (Sikder & Alam, 2003). Dhaka, as a densely populated and infrastructurally old city, remains under severe risk. The loss of life would be calamitous, and economic loss would be in billions of dollars due to widespread destruction of infrastructure, homes, and businesses if a large earthquake occurred. In conclusion, Bangladesh's 500-year seismic history is a pointer to the highly real threats that are faced in the country because of its complex tectonic environment. Earthquakes of various magnitudes have caused widespread destruction and loss of life, particularly in densely populated cities such as Dhaka. As the nation continues to urbanize, there is an urgent need for seismic hazard assessment in more detail, particularly concerning vulnerable building types such as Unreinforced Masonry (URM) buildings. Also, the lack of an entire earthquake damage database in Bangladesh, as opposed to the extensive history of records in developed countries, demonstrates the need to develop localized seismic risk assessment methods to adapt to the existing conditions in Bangladesh (Ali, 1999).

2.4.1 Tectonic Setting of Bangladesh

Bangladesh lies on the northeastern edge of the Indian Plate, which is being subducted to the north by the Eurasian Plate and to the east by the Burmese Plate. The area's tectonic situation involves complicated interactions that cause different earthquake risks. The tectonics in the region are controlled by the continuous collision between the Indian and Eurasian Plates, which is producing the uplift of the Himalayas and seismicity in the area. Bangladesh is surrounded and affected by these big tectonic plates:

- The Himalayas: Up north, where India crashes into Eurasia, so Bangladesh got the Himalayas. This area shakes a lot!
- The Shillong Plateau: To the northeast, there's this raised-up block called the Shillong Plateau, and it's got some significant shaking going on too.
- Indo-Burman Ranges: East of Bangladesh, it is characterized by the oblique subduction of the Indian Plate beneath the Burmese Plate and has produced the Indo-Burman accretionary prism.

These tectonic settings have formed several active faults within and around Bangladesh, as outlined in Figure 2.8, which can generate moderate to great earthquakes.

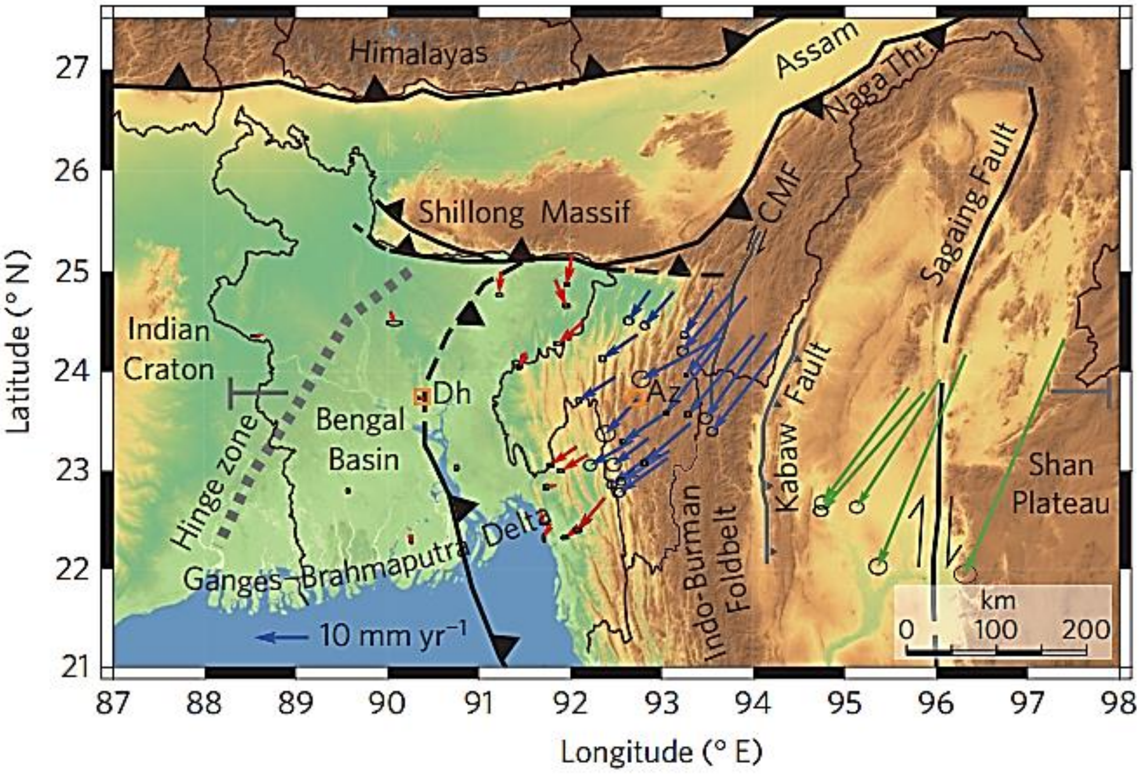


Fig. 2.8 Topographic map of the Ganges–Brahmaputra delta and Indo-Burman foldbelt showing GPS velocities (Steckler et al.).

2.4.2 Active Faults in and Around Bangladesh

Figure 2.10 illustrates the geographical locations of the main fault lines of Bangladesh, as documented in Banglapedia. The map delineates significant tectonic elements like the Dauki Fault, the Tripura Fold Belt, and the Assam Fault Zone, which strongly contribute to the seismicity of the area. The faults highlight the complex interaction among the Indian, Eurasian, and Burmese tectonic plates. The map is an essential tool in seismic hazard comprehension and earthquake-resilient structural planning. Its availability establishes the importance of regional geology studies in assessing earthquake hazards specific to Bangladesh. The most critical active fault in the region is the Dauki Fault, which follows the south margin of the Shillong Plateau. It is a significant strike-slip fault with a thrust component, accommodating the Indian Plate's northeastward movement. The Dauki Fault is identified as a focal zone for massive earthquakes, and seismicity records are available.

- Seismic Potential: Based on studies, the Dauki Fault can generate earthquakes of a maximum of 8.0 magnitude (Steckler et al.). The ongoing convergence between the Eurasian and Indian Plates triggers the fault.

The Madhupur Fault is an active strike-slip fault that traverses the central part of Bangladesh. It is associated with the Madhupur Tract, an uplift block in the Bengal Basin. The fault is considered active and poses a high seismic risk to highly populated regions of central Bangladesh.

- Seismic Potential: Geological studies and past data indicate that the Madhupur Fault has generated medium-sized earthquakes in the past. Since the fault lies immediately adjacent to massive city centers like Dhaka, the hazard potential increases.

The Bogra Fault, located in the northwestern part of Bangladesh, is the second significant active fault. It is associated with the northward propagation of the Dauki Fault system and is a strike-slip fault with minor thrust movement.

- Seismic Potential: Bogra Fault has proven to be a seismically potential area with the ability to cause moderate-sized earthquakes having magnitudes up to 7.0 (Steckler et al., 2016). The fault movement is attributed to the tectonic interaction of the Indian Plate with the underlying crustal frameworks.

The Chittagong-Tripura Fold Belt, located in the eastern part of Bangladesh, is a zone of intense tectonic deformation. The fold belt is characterized by a series of east-west-trending anticlines and synclines and correlates with active thrust faults.

- Seismic Potential: Thrust faults of the Chittagong-Tripura Fold Belt can produce moderate to large earthquakes. Seismic history indicates that the region has seen several significant seismic events, including the 1762 Arakan earthquake that is estimated to have been 8.5 (Mw) in magnitude (Akhter, 2010).

Figure 2.9 indicates the geographical spread of major fault lines in the country. The faults indicate the tectonic vulnerabilities of Bangladesh, particularly the areas where seismic activity is most likely to take place. The figure is a valuable reference in delineating the likelihood of earthquake hazards, helping in disaster preparedness and urban planning. The figure relies on Banglapedia data, which is a reliable repository of information regarding Bangladesh.

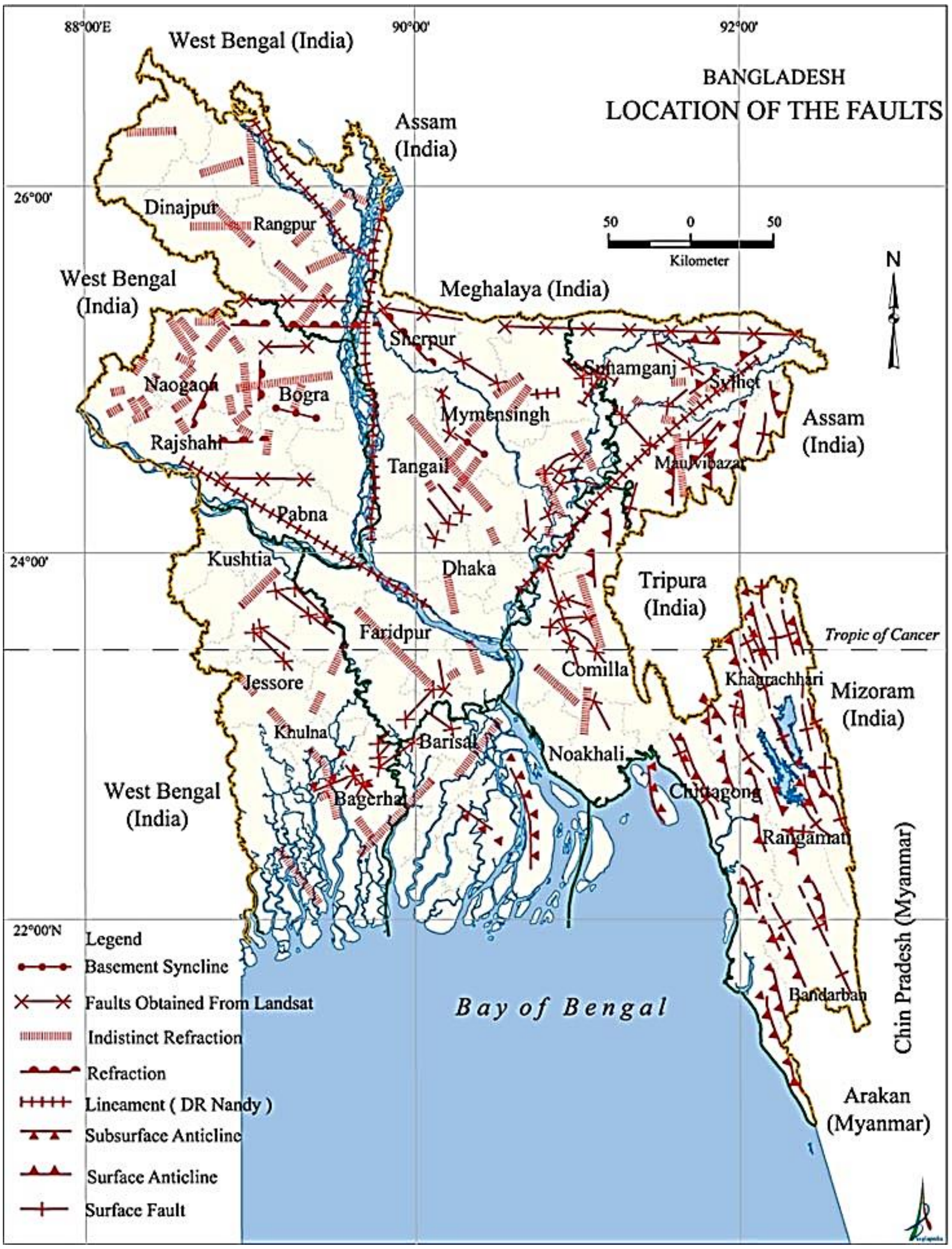


Fig. 2.9 Location of the faults in Bangladesh (Source: Banglapedia, https://en.banglapedia.org/index.php/Fault).

2.5 Seismic Risk at Dhaka

The seismic risk of Dhaka, the capital of Bangladesh, has been a serious concern as it is highly populated and contains numerous unreinforced masonry (URM) buildings. URM buildings, making up approximately 30% of buildings in Dhaka, are highly susceptible to collapse in an earthquake. Buildings made of brick and mortar without steel are less effective at withstanding the sideways forces of an earthquake. Back in 2009, the Bangladesh government's disaster program (CDMP) checked out the earthquake risks in Dhaka. That study looked at what might happen if a big one hit, and the predictions were scary. The CDMP estimated that around 72,000 buildings in Dhaka could fall apart in a significant earthquake. That's about 22% of all buildings. What's even worse is that there are many old, weak buildings that are likely to crumble.

During a major earthquake, the destruction of such buildings would result in extensive damage, thereby overwhelming the city's emergency response mechanisms (CDMP, 2009). Apart from complete collapses, the CDMP report further estimated that up to 158,000 buildings, or roughly 49% of the city's infrastructure, would suffer moderate to severe damage if an earthquake were to hit. Because URM structures comprise a large portion of the city's infrastructure, the potential for significant damage is high. They are inherently susceptible because they lack strengthening, and their brittle nature prevents them from flexing or dissipating energy from seismic motion. Their fall would bring catastrophic destruction, intricate rescue operations, and significantly hinder the city's ability to recover (CDMP, 2009). The human loss of a high-level earthquake would be catastrophic. The CDMP estimates have up to 88,000 people at risk of being killed in a high-level earthquake in Dhaka. Most of these deaths would be due to the URM building collapses, which are dense within densely populated areas. The limited roads and condensed format of the buildings would lead to a domino effect, wherein collapsed buildings might trap thousands of individuals under debris. With 1.3% of the city population under threat of death, the situation serves as a clear pointer to the necessity to address the seismic risk to the city (CDMP, 2009). The economic impact of such a disaster would be no less debilitating. According to CDMP estimates, economic damage from a catastrophic earthquake would be up to 12.7 billion USD or about 13.4% of the GDP of Bangladesh in 2009. A significant proportion of this economic loss would be caused by the collapse and damage of URM buildings, which are prevalent in Dhaka's building stock. Since Dhaka is the financial hub of Bangladesh, an earthquake would have enormous economic repercussions, not only for the city but for the country's economy. That is why it is significant that education investments be made into retrofitting such vulnerable buildings and updating building codes to prevent this calamitous event from occurring (CDMP, 2009).

2.5.1 Earthquake Vulnerability

Dhaka's earthquake vulnerability has been reported extensively in several global hazard vulnerability ratings. Stanford University Earthquake Disaster Risk Index (EDRI) 2010 ranked Dhaka as one of the 20 most at-risk cities globally (Stanford University, 2010). The World Bank's Global Urban Risk Index 2013 also marked Dhaka as having a high earthquake risk and ranked it among the top five earthquake-vulnerable South Asian cities (World Bank, 2013). The factors contributing to the seismic vulnerability of Dhaka are numerous, including a high population, poor building codes, and a shortage of earthquake-resistant infrastructure. The density of URM structures, which are brittle and highly susceptible to seismic forces, contributes significantly to the vulnerability of the city. In the event of an earthquake, loss of human life and economic losses would be catastrophic, as envisioned by both Stanford and World Bank reports. Urbanization of Dhaka has resulted in the expansion of slums and poorly constructed buildings, most of which were not intended to meet existing seismic building codes. These substandard buildings are concentrated in residential neighborhoods, increasing the number of widespread casualties in the event of an earthquake. Particularly, URM buildings, since they are constructed with ancient methods, lack structural support to withstand even minute seismic movements (Khan et al., 2017). The city's infrastructure, bridges, and roads are also prone to earthquake destruction. Most of the city's infrastructure is old and developed without seismic forces incorporated in its design. During an earthquake, road and bridge collapse would badly disrupt response operations, and rescue teams would find it challenging to reach the worst-hit zones (Bilham & England, 2001).

2.5.2 Seismic Vulnerability in Dhaka's URM Buildings

URM buildings pose a unique challenge of seismic vulnerability. URM buildings, common everywhere in Dhaka, consist of brittle materials that cannot flex or dissipate seismic energy. Lack of support in URM buildings makes them extremely dangerous since they can collapse wholly and immediately when an earthquake strikes (Steckler et al., 2016). The majority of URM buildings in Dhaka have been constructed without adhering closely to seismic codes, particularly in the case of slums, where building codes are not enforced. The buildings are often built with poor materials, and no one really takes care of them. This makes them more likely to get messed up if there's an earthquake (CDMP, 2009). People have tried using the Vulnerability Index Method to figure out how likely these URM buildings are to be damaged during an earthquake. This approach assesses factors such as the building's strength, material composition, and maintenance quality (Khan et al., 2017). However, implementing this in Dhaka requires effort, as everyone constructs differently, and the city's building regulations aren't always adhered to by ordinary people.

2.5.3 Seismic Hazard Assessment of URM Buildings

Back in 2009, the CDMP's seismic hazard assessment pointed out that Dhaka really needs to reinforce its unreinforced masonry (URM) buildings. Otherwise, a quake could cause significant damage. Dhaka is located near several active faults, including the Madhupur and Dauki faults, which increase the likelihood of moderate to strong earthquakes. These faults being so close means we could see a big quake in the next 20 years (Steckler et al., 2016). Fixing up URM buildings with steel or concrete would really help them withstand earthquakes better. But we also need to make sure all new buildings follow the latest building codes and have earthquake-resistant designs. If not, Dhaka will still be at high risk from quakes, mainly because there are still so many URM buildings all over the city (CDMP, 2009).

CHAPTER 3: DEVELOPMENT OF RAPID SEISMIC ASSESSMENT METHOD (RSAM)

3.1 General

Firstly, the process begins with a thorough examination of the building. The inspector roams the walls, roof, foundation, and other key parts. They're checking for any signs of trouble, such as cracks or other indicators that the building might not withstand an earthquake well. Besides the building's condition, the inspector also considers factors such as its age, the quality of its initial construction, and any prior work that may have been done. The Rapid Seismic Assessment Method (RSAM) helps determine the likelihood of unreinforced brick buildings being damaged in an earthquake. Experts dealing with earthquake risks use this method. It mainly involves looking at the building and is suitable for engineers and other professionals. Basically, if the URM walls can handle more than what an earthquake would throw at them (based on Equations 3.1 and 3.2), then the building should be okay. Equation 3.3 considers several key factors, including the building's type, number of floors, wall shape, wall thickness, opening sizes, unusual shapes, water buildup potential, age of the building, and overall appearance.

3.2 Fundamentals of Seismic Evaluation Procedure

Firstly, fundamental data for structural and non-structural parameters must be collected during a site visit to the building. Begin by inspecting the roof, walls, and foundation for any cracks, bulges, or signs of wear. This can indicate potential problems that may arise when things get shaky, and this approach was first introduced in the user’s manual of Housing and Building Research Institute (HBRI) by Bhuiyan and Islam (2022) and in further improved research works by Islam et al. (2022, 2024). Considering the building's construction quality, its age, and any previous work done, these factors all make a difference. Now, there's a method called the Rapid Seismic Assessment Method (RSAM) that’s designed to determine how buildings made of brick will handle an earthquake. It uses what you see during these checks to figure out the risk. The RSAM's basic principle is based on the correlation between the seismic capacity of the URM walls and the seismic demand applied to the building. The strength of a brick building during an earthquake depends on the strength of each of its walls in a sideways direction. You can find a wall's sideways strength by multiplying its cross-section by its shear strength, like in Equation 3.1.

$$\textit{Seismic Capacity} = \tau_{wi} . A_{wi} \tag{3.1}$$

Where, τ_{wi} is the average shear strength of an individual masonry wall, A_{wi} is the in-plane cross-sectional area of the wall.

Equation 3.2. This shows the seismic demand, which is the product of the total building weight (W), including both dead loads and live loads, the response acceleration (C_a), and the reduction factor (D_s) considering the building ductility.

$$\textit{Seismic Demand} = C_a . D_s . W \tag{3.2}$$

Then, for the safety of the building, the inequality as given in Equation 3.3 should satisfy the Seismic Capacity ≥The Seismic Demand

$$\tau_{wi}.A_{wi} \geq C_a.D_s.W \tag{3.3}$$

This ensures that the building's seismic capacity is sufficient to withstand the expected seismic forces, thus providing a measure of its overall seismic resilience.

3.3 Rapid Seismic Assessment Method

For measuring the seismic performance of an unreinforced masonry (URM) building, one of the most critical parameters is the Basic Seismic Capacity Index. The seismic capacity of a URM building is all about how much sideways force each wall can handle. The stability of a wall depends on its size and shear strength, which can be determined using Equation 3.1. Please think of the seismic capacity index as a simple way to see how well a building can stand up to earthquakes, considering its size. To get this index, you divide the building's sideways strength by its floor area. This number indicates how well the building can withstand earthquake forces, based on its size. You can find the lowest acceptable seismic capacity index for a URM building by dividing its sideways capacity by the total floor area, as shown in Equation 3.4.

$$\text{Basic Seismic Capacity Index} = \frac{Seismic\ Capacity}{Total\ Weight} = \tau_{wi}\frac{A_{wi}}{N_s.A_f.w} \tag{3.4}$$

N_s is the number of floors, A_f is the floor area, and w is the weight per floor area of the building. This index basically adjusts the building's ability to handle earthquakes based on its floor area and weight, so you get a measure of how earthquake-resistant it is for its size. This helps compare buildings of different sizes and weights to determine if a building is strong enough sideways, considering its size and how it's built.

3.4 Seismic Capacity Modification Factors

Seismic capacity modification factors, or F factors, are super important in seismic design. They tweak a building's theoretical seismic capacity to make it more realistic in the event of an earthquake. Basically, they help include any vulnerabilities that normal calculations miss. By using these factors, engineers can more easily check and improve how buildings handle earthquakes, which makes them safer for unreinforced masonry (URM) buildings. That is, buildings made of brick without any rebar applying these F factors is a must. URM buildings don't handle earthquake forces well because they're stiff and brittle and lack the reinforcements that help buildings absorb energy. So, they need a more thorough check to see how they'll hold up during a quake. The F factors for URM buildings aim to capture all aspects that make them vulnerable to seismic loading. These factors modify the theoretical seismic capacity, which is based on ideal scenarios, to reflect more real-world situations. The main F factors are listed below.

3.4.1 Wall rigidity (F_{OP})

Opening in a load-bearing URM wall has a significant effect on its strength and stiffness. Motivated by the results obtained from the numerical analysis by Liu and Crewe (2020) using finite element (FE) macro model, pier wall analysis, and experiments of masonry wall samples CERL TR-02-1 by Alchaar (2002), other FE models and analysis details are shown in Table 3.1- 3.2 and Figure 3.1. The concept of the damage plasticity model was idealized from the finite element model-based work by Islam et al. (2020). Corresponding results associated with the stiffness degradation factor (F_{OP}) as a function of opening area (OP) of the wall are presented in Figure 3.2.

Table 3.1 Compressive and tensile behavior of brick material.

Damage Plasticity Model (Abaqus)			
Compressive Behavior		Tension Behavior	
Yield stress (MPa)	Inelastic strain	Yield stress (MPa)	Cracking strain
3.549	0	1.06	0
3.8163125	0.0004075	0.8	1.30E-04
3.8845625	0.000935	0.65	0.00025
3.696875	0.0015525	0.48	0.00052
1.967875	0.0033325	0.42	0.00064
1.4958125	0.003995	-	-

Table 3.2 Geometric details of FE simulation walls.

	E	F	G	H
Length (mm)	1500	1500	1500	1500
Height (mm)	1280	1280	1280	1280
Thickness (mm)	110	110	110	110
Vertical Pressure (MPa)	0.17	0.15	0.12	0.11
Opening (%)	10.41667	14.58333	19.0588	27.0833
A.R.	0.853	0.853	0.853	0.853

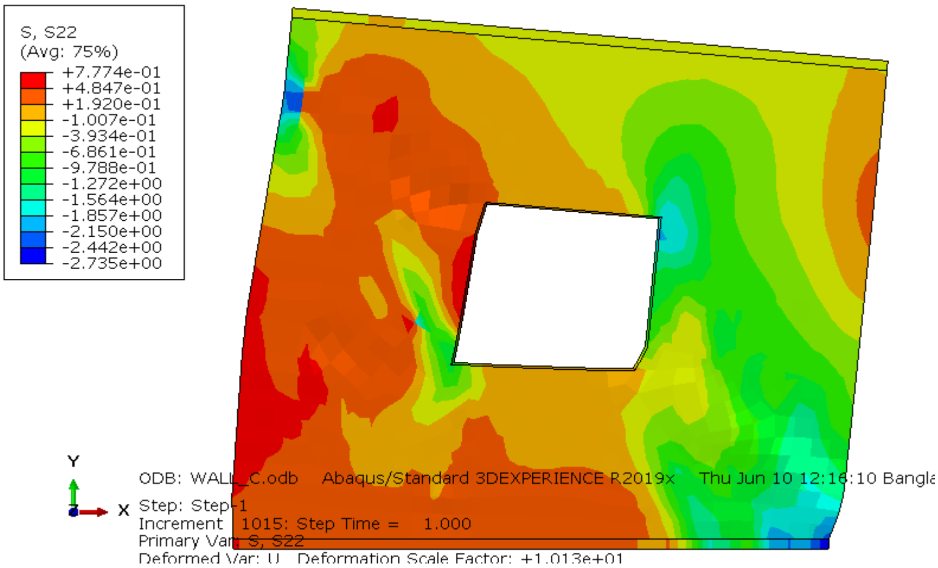


Fig. 3.1 (a) Macro FE model for sample F.

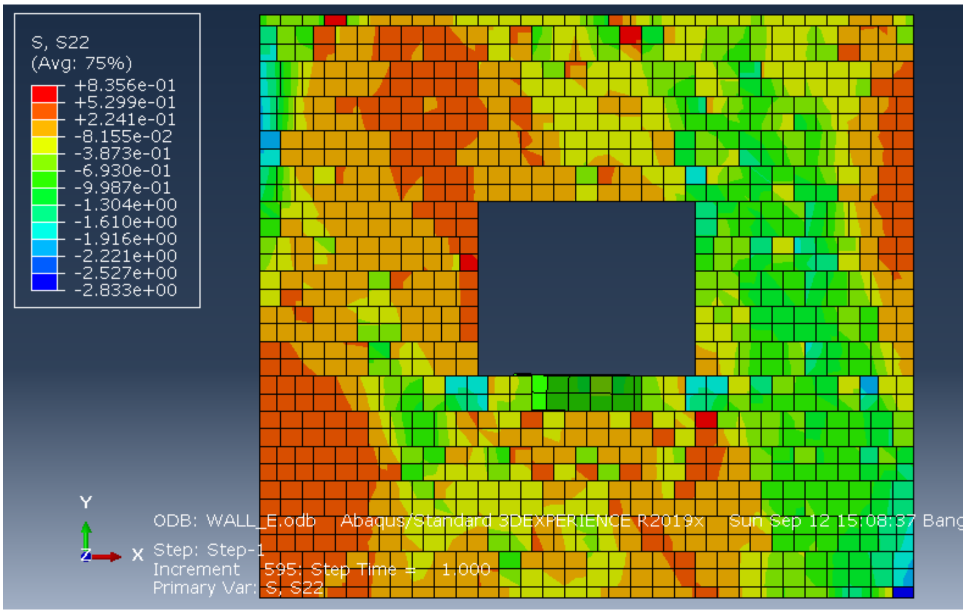


Fig. 3.1 (b) Simplified micro FE model for sample F.

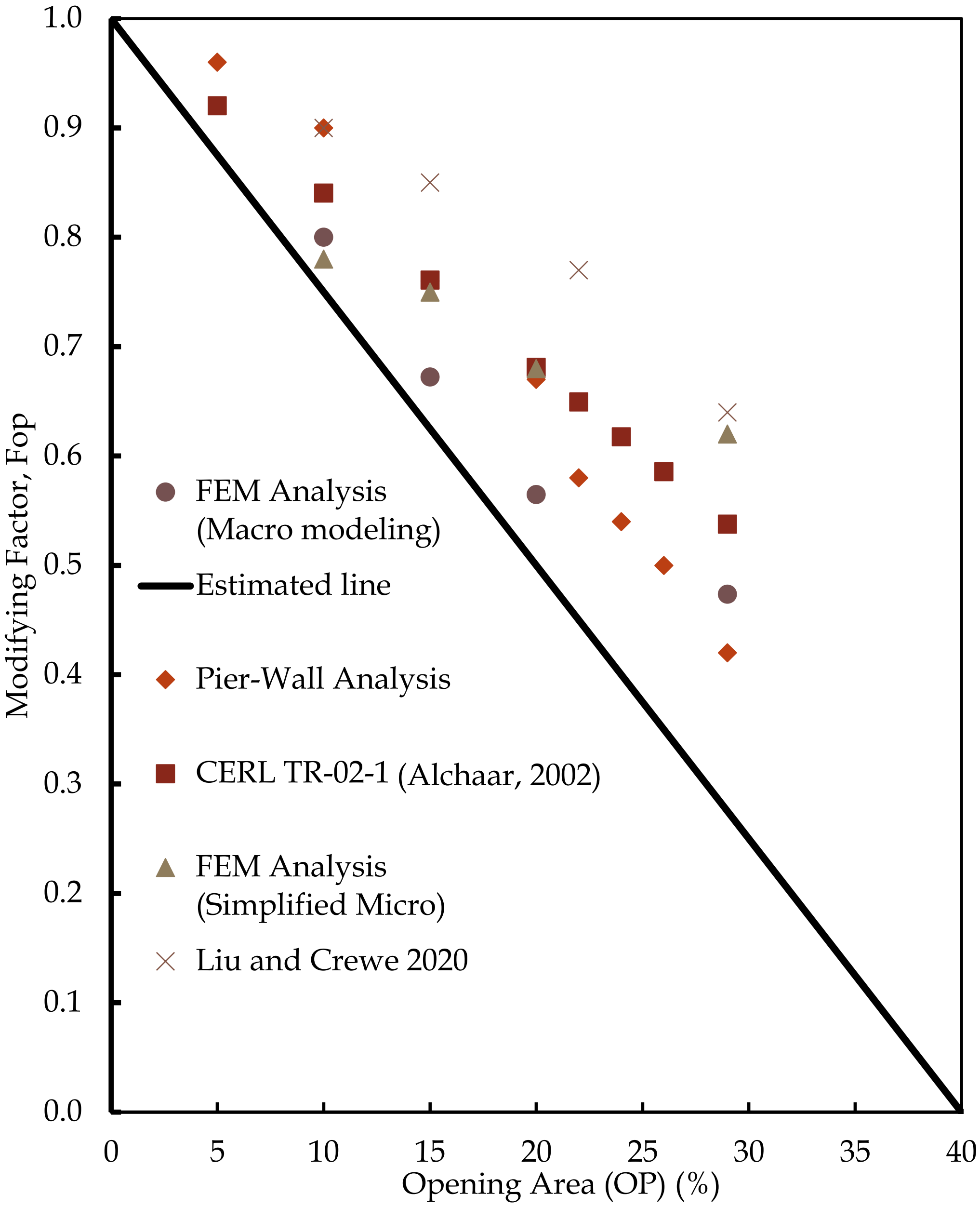


Fig. 3.2 Effect of wall opening on stiffness degradation.

3.4.2 Wall slenderness (F_{SR})

The slenderness ratio affects the stability of URM walls during an earthquake, as observed in the Gorkha earthquake in 2015. Hence, it is a vital parameter to address out-of–plane stability of URM walls. The increase in slenderness ratio decreases the strength of URM walls by Chudal and Maskey (2019). Based on out-of-plane failure with marginal residual strength of URM walls, the strength reduction factor (F_{SR}) as a function of slenderness ratio (SR) of URM walls and the transition limits of the slenderness ratio (SR) in Figure 3.3 are developed and proposed from set of data based on the experimental and numerical findings by Chudal and Maskey (2019). The study showed that URM walls maintain full strength up to SR ≈ 10, beyond which strength gradually decreases due to increasing out-of-plane instability, reaching near-zero strength around SR ≈ 25. The proposed strength reduction curve (F_{SR}) follows the trend of their results, with strength remaining constant initially and then linearly decreasing.

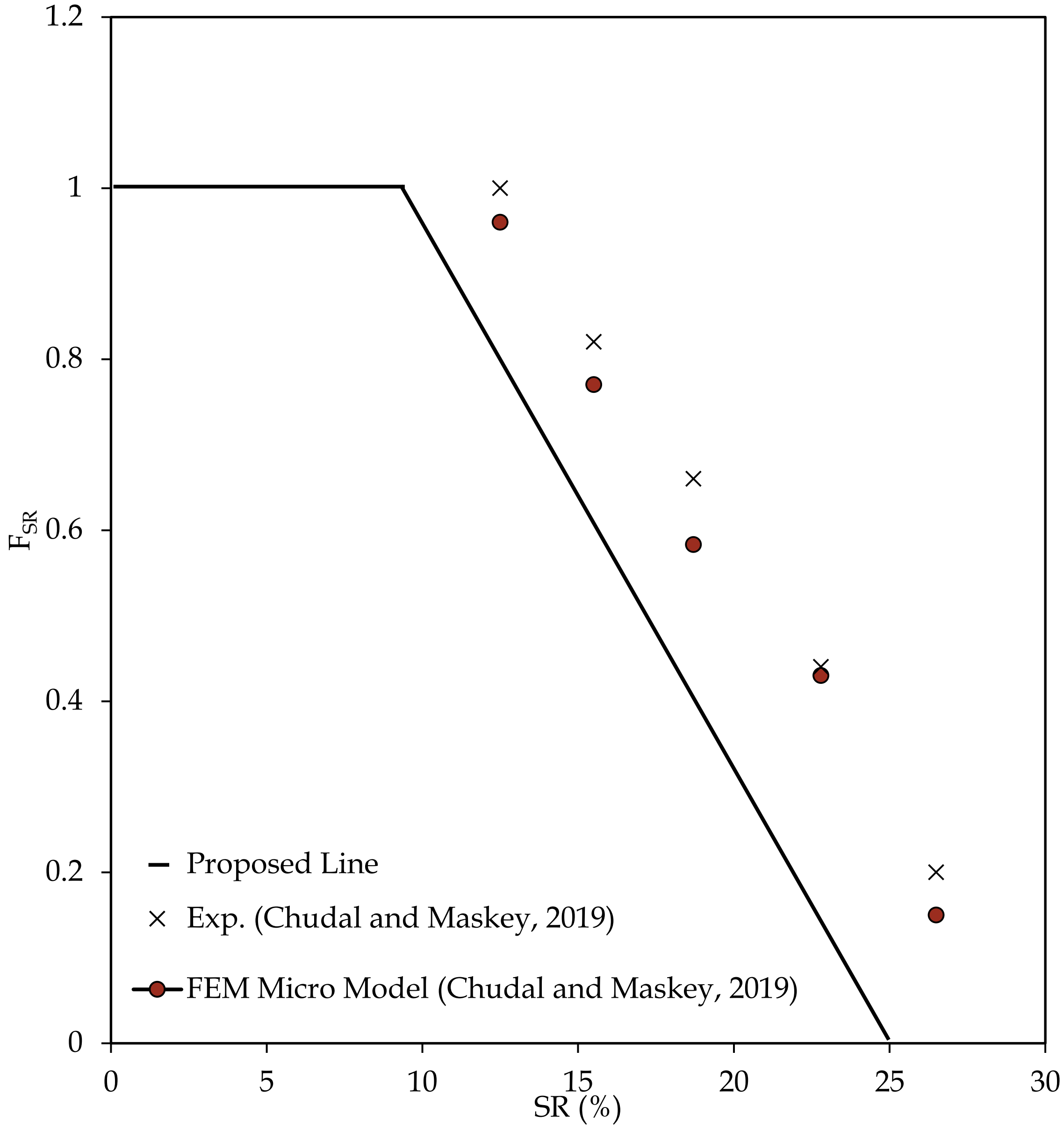


Fig. 3.3 Effect of the wall's slenderness ratio on strength reduction.

3.4.3 Aspect ratio (F_{AR})

The aspect ratio of the URM wall has a significant effect on its lateral strength, stiffness, and failure modes. Based on experimental results of URM walls by Akhaveissy (2013) and FE analysis results of individual URM walls, the strength reduction factor (F_{AR}), the relationship between the aspect ratio (H_w/L_w) of an unreinforced masonry (URM) wall is shown in Figure 3.4, where H_w represents the height of the wall. L_w represents the width of the wall. Table 3.3 shows the effect of aspect ratio (AR) on failure modes and lateral strength of URM walls from experimental results of URM walls by Liu and Crewe (2020).

Table 3.3 Effect of aspect ratio (AR) on failure mode and lateral strength of URM walls.

Aspect Ratio (AR)	Failure Mode Types	Factors in Terms of Strength
Up to 0.5	Bed Joint Slide	0.8
0.5 to 2.0	(Flexure, Toe Crushing, Diagonal, Bed Joint Slide) mixed modes	Linear Interpolation
2.0 or above	Rocking and/ or Rocking with Toe Crushing	0.25

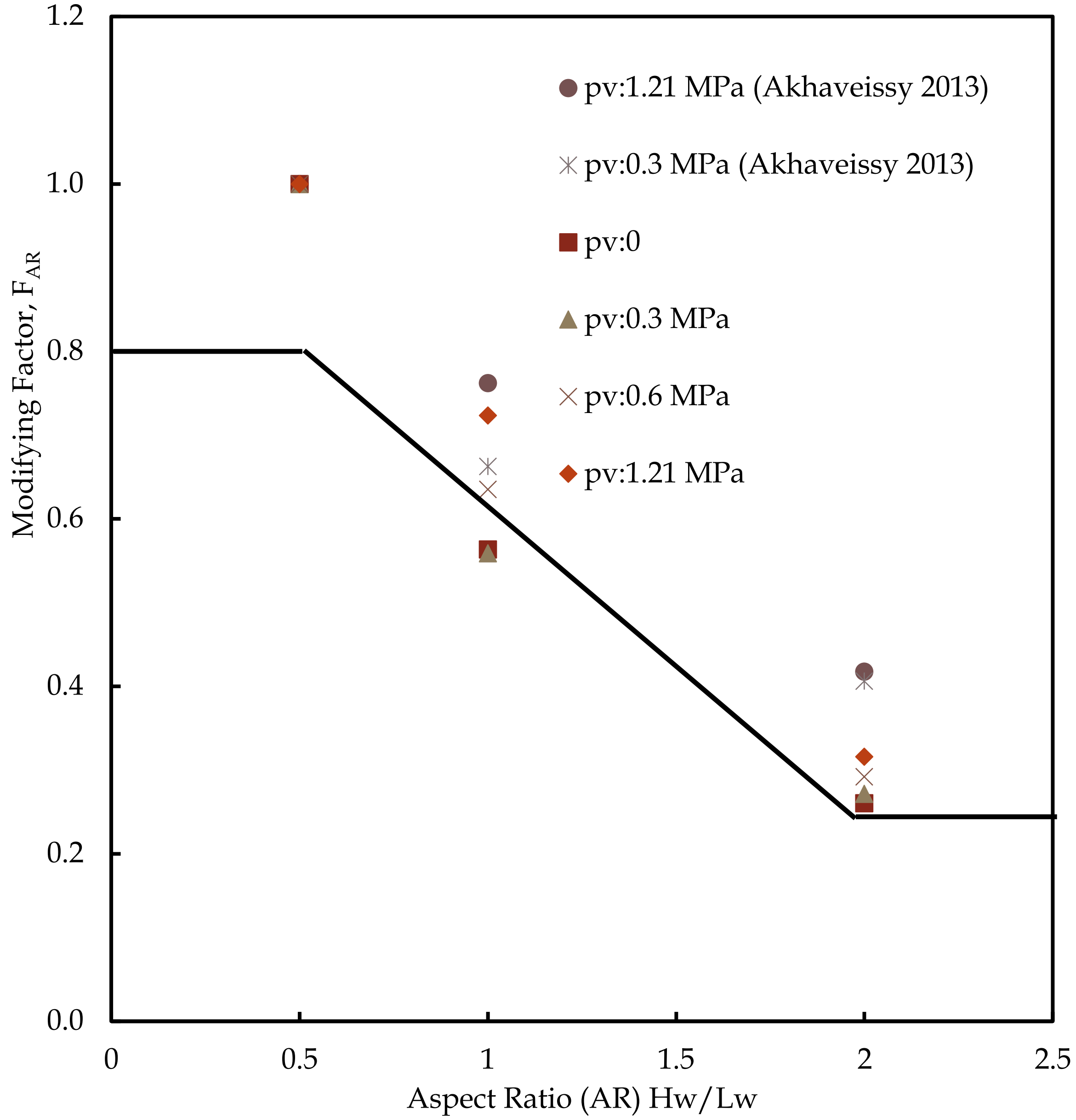


Fig. 3.4 Effect of the wall's aspect ratio on strength reduction.

3.4.4 Deterioration effect (F_D)

The URM walls should be free from any deterioration due to environmental effects. According to FEMA 307 (1998) and FEMA 310 (1998) guidelines, the visible crack width of 1.56 *mm* is defined as moderate, and that of 3.125 *mm* is defined as severe deterioration. The weightage factor for the effect of deterioration (F_D) is given in Table 3.4.

3.4.5 Vertical irregularity (F_{VI}) and Horizontal irregularity (F_{HI})

The irregularity factor is used to modify the basic seismic capacity of the structure by considering the effects of shape complexity and stiffness unbalance distribution, among other factors, on the seismic performance of the URM building, as determined by engineering judgment. Weightage factors for vertical irregularity (F_{VI}) and horizontal irregularity (F_{HI}) are given in Table 3.4.

3.4.6 Building Age (F_T)

The building age factor (F_T) evaluates the effects of structural defects such as cracking, deflection, aging, and the like, on the seismic performance of a URM building. The weightage factor for the building age effect is given in Table 3.4.

Table 3.4 Weightage factors for deterioration, vertical and horizontal irregularities, and building age effects of URM walls are considered in the study (ASCE 41(2017), FEMA 356 (2000), HBRI (2022a, b)).

	Regular		Irregular
F_{IV}	1		0.8
F_{IH}	1		0.9
F_D	Good	Moderate	Severe
	1	0.75	0.6
F_T	New (<15yrs)	Moderate (15 to 30yrs)	Old (>30yrs)
	1	0.95	0.9

3.4.7 Pounding Effect (F_p)

Pounding effects can occur when two adjacent buildings meet each other during an earthquake because of proximity and differences in dynamic properties. It can alter the basic response of the building to ground motion and impart additional inertial loads and energy to the building from the adjacent structure, leading to concentrated and potentially damaging forces (FEMA 356, 2000). The strength reduction factor (F_P) evaluates the pounding effects for unreinforced masonry (URM) buildings under seismic loading. The reduction in the F_P factor is typically based on empirical data and may vary depending on the specific design code and the level of seismic hazard in the region (FEMA 356, 2000; ASCE 41, 2017). For example, the FEMA 356 (2000) guidelines recommend reducing the F_P factor by 5% for a low-level pounding effect, 10% for a moderate-level pounding impact, and up to 25% for a severe-level pounding effect (FEMA 356, 2000), as given in Table 3.5. The ASCE 41(2017) standard recommends reducing the FP factor by 10% for minor bumping and up to 30% for severe bumping.

Table 3.5 Weightage for possible pounding issues in existing URM buildings (from ASCE 41(2017) and FEMA 356 (2000)).

Factor	No Risk	Low-Level	Moderate-Level	Severe-Level
F_P	1	0.95	0.9	0.75

These seismic strength reduction factors help tweak the design forces for unreinforced masonry buildings in seismic zones, so they better reflect how they'll perform during earthquakes. The exact numbers used for these factors can change based on local building codes, standards, and common engineering practices.

3.5 Rapid Seismic Index (I_{RS})

Assessing the performance of old brick buildings in earthquakes is challenging. It involves combining complex and straightforward methods to determine whether a structure can withstand shaking. Since these buildings are old and not reinforced, determining their earthquake resistance is challenging. So, we must be extra careful when we check them to see if they are safe during an earthquake. The simplified basic seismic capacity index (Equation 3.4) of existing unreinforced masonry buildings, after due consideration of the influence of strength modification factors, can be obtained using the Rapid Seismic Index (I_{RS}) as shown in Equation 3.5.

$$I_{RS} = [\textstyle\sum_{i=1}^{n}(\tau_{wi}\frac{A_{wi}}{N_s.A_f.w}.\ F_{OPi}.\ F_{SRi}.\ F_{ARi}.F_{Di})].\ F_{IV}.F_{IH}.F_T.F_P \quad ; \ n = nos.of\ walls \quad (3.5)$$

Where$A_{wi} = (t_w.l)_i$and$A_f = l_x.l_y$: $t_w$and l are the average thickness and length of the i^{th} wall, l_x and l_yIndicate the average length of the building in x and y directions, respectively. The strength modification factors inside of [] shall apply to individual walls, and those outside of [] shall apply to the whole building. The average shear strength of a URM panel comprises the average bed-joint shear strength and the frictional force due to the compressive force applied to it. For URM components, the average shear strength of masonry, τ_{wi}, Shall be measured using the in-place shear test conducted by Castillo et al. (2008). The general form of the average shear strength of masonry can be obtained using Equation 3.6 as below-

$$\tau_{wi} = \tau_0 + \mu f_{ae}, \quad (3.6)$$

Where τ_0 is the bed-joint shear strength, μ is the friction coefficient, and f_{ae}This is the gravity compressive stress, which is applied to the wall. Instead of material tests, default values of the bed-joint shear strength of URM wall shall be taken not to exceed 27 psi for running bond masonry in good condition, 20 psi for running bond masonry in fair condition, and 13 psi for running bond masonry in poor condition (Castillo et al. 2008). The μ and τ_0 values are conservatively assumed to be 0.40 and 0.10 MPa, respectively. When we check how unreinforced brick walls hold up during earthquakes, we examine several key factors to assess their strength. One important thing is how strong the mortar is between the bricks. This tells us how well the wall can handle sideways shaking from an earthquake.

a) Bed-Joint Shear Strength and Friction Coefficient

The strength of a masonry bed joint depends on factors such as the type of masonry, the condition of the wall, and its composition. It's basically the most shear force it can take before breaking. Knowing this strength is crucial for ensuring walls can withstand earthquakes. Friction is also key; it tells you how well the wall resists sliding. And, of course, how much weight is pressing down on the wall matters too, because that affects how much shear force it can handle.

b) Default Bed-Joint Shear Strength Values

Whenever there are no tests on specific materials, default bed-joint shear strength values for URM walls are utilized to estimate the performance of the wall conservatively. The default values are found based on masonry condition and are categorized as follows:

- Good Condition: For good condition running bond masonry, bed-joint shear strength is used as a maximum of 27 psi (pounds per square inch). This is for well-maintained masonry with minimal degradation or deterioration.
- Fair Condition: For fair condition running bond masonry, bed-joint shear strength is reduced to 20 psi. This is for some wear and tear or slight defects affecting the performance of the masonry.
- Poor Condition: If the running bond masonry is in bad shape, the bed-joint shear strength goes down to 13 psi. This lower number indicates widespread damage that's weakening the masonry.

These default values give a safe estimate of the bed-joint shear strength. This way, when we check how the building holds up during an earthquake, we're on the safe side, and the results are conservative.

c)Default Values for Shear Strength Parameters

When buildings are safe against major earthquakes, here are typical shear strength and friction numbers to use:

- Bed-Joint Shear Strength: To be super safe, we usually say it's 0.10 MPa. This indicates the strength of the joints, which helps determine how well the wall can withstand shearing forces.
- Friction Coefficient: We usually guess the friction coefficient is 0.40. This number roughly estimates how well the bricks stick to each other. It helps determine the likelihood of the wall sliding during earthquakes.

d) Practical Implications

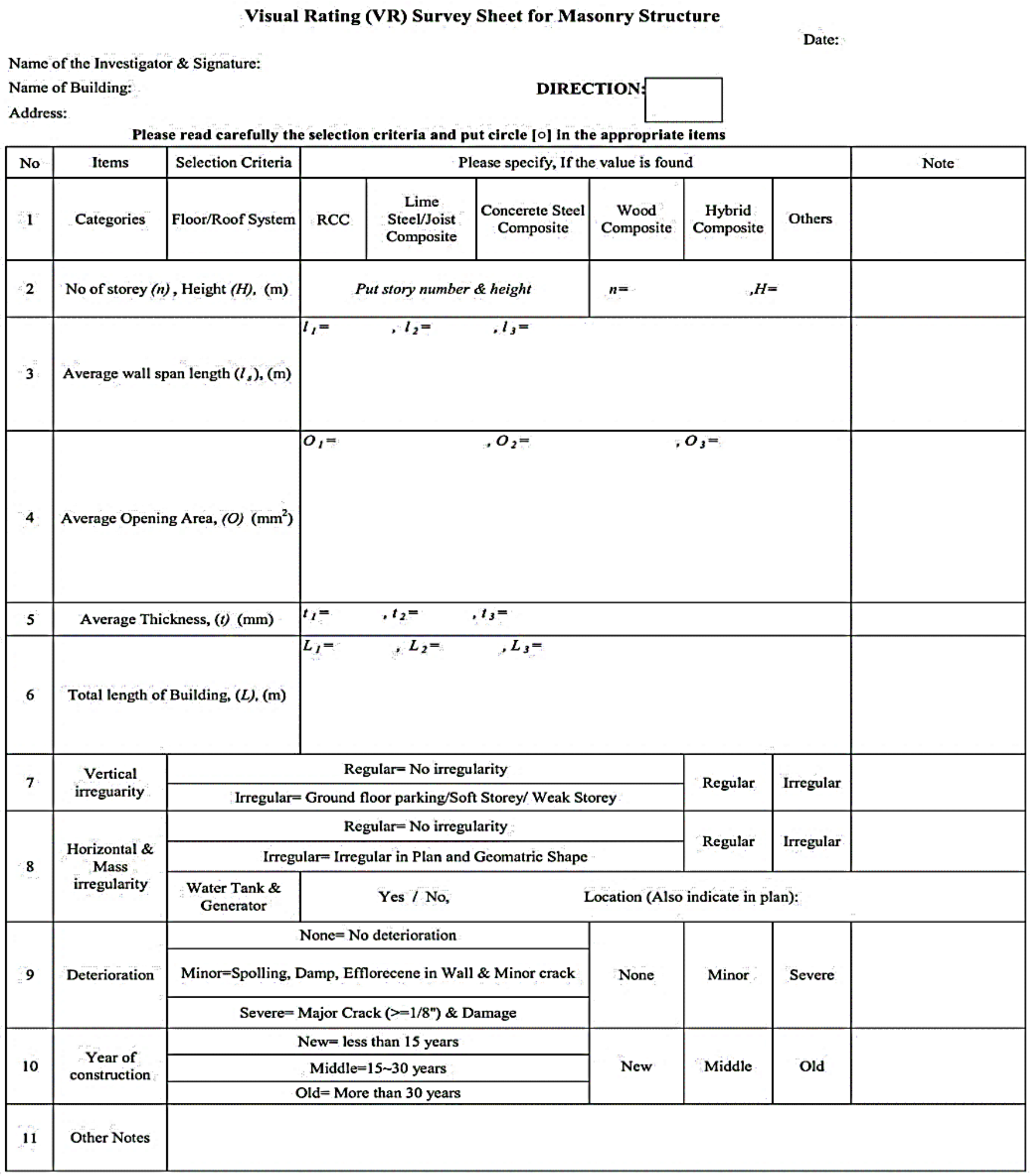
Using default values in this application helps to make sure the seismic checks are both safe and realistic. It considers different situations and any uncertainty about how strong the materials are. Because the numbers are already set, engineers and safety experts can determine the strength of brick walls, even if they haven't run special tests on the materials. They can be reasonably sure of their results. To sum things up, bed-joint shear strength and friction influence how brick walls stand up to earthquakes. Those default numbers, which change based on the masonry's condition and are adjusted to be on the safe side, are a must to make sure the checks are solid and spot-on. It helps you assess how well the building can withstand earthquake forces. With this knowledge, you can decide if you need to fix or shore up the walls to make them stronger against earthquakes.

3.6 Development of RSAM Survey Sheet

The RSAM survey sheet is great for quickly checking how likely old brick buildings are to be damaged in an earthquake. It helps inspectors gather key info in an organized way. This includes details about the building's structure, what it's made of, and any weak spots they see, focusing on each main direction of the building. The sheet supports consistency and reliability of assessments by presenting clear instructions and pre-defined fields of data, which enable quick but thorough evaluations. Through effective acquisition of the significant parameters, it allows decision-making for enhancing the seismic resilience of URM buildings.

3.6.1 Data Collection Survey Datasheet

Completion of the survey data sheet is one of the significant tasks for the application of the RSAM. This method considers a quick inspection of buildings over a short period of time. The survey datasheet is attached below with detailed instructions for each part and parameters of the RSAM method. A data sheet shall be duly filled in each principal direction in Figure 3.5, and an on-site hand sketch can be performed in Figure 3.6.



Visual Rating (VR) Survey Sheet for Masonry Structure

Date:

Name of the Investigator & Signature:

Name of Building:

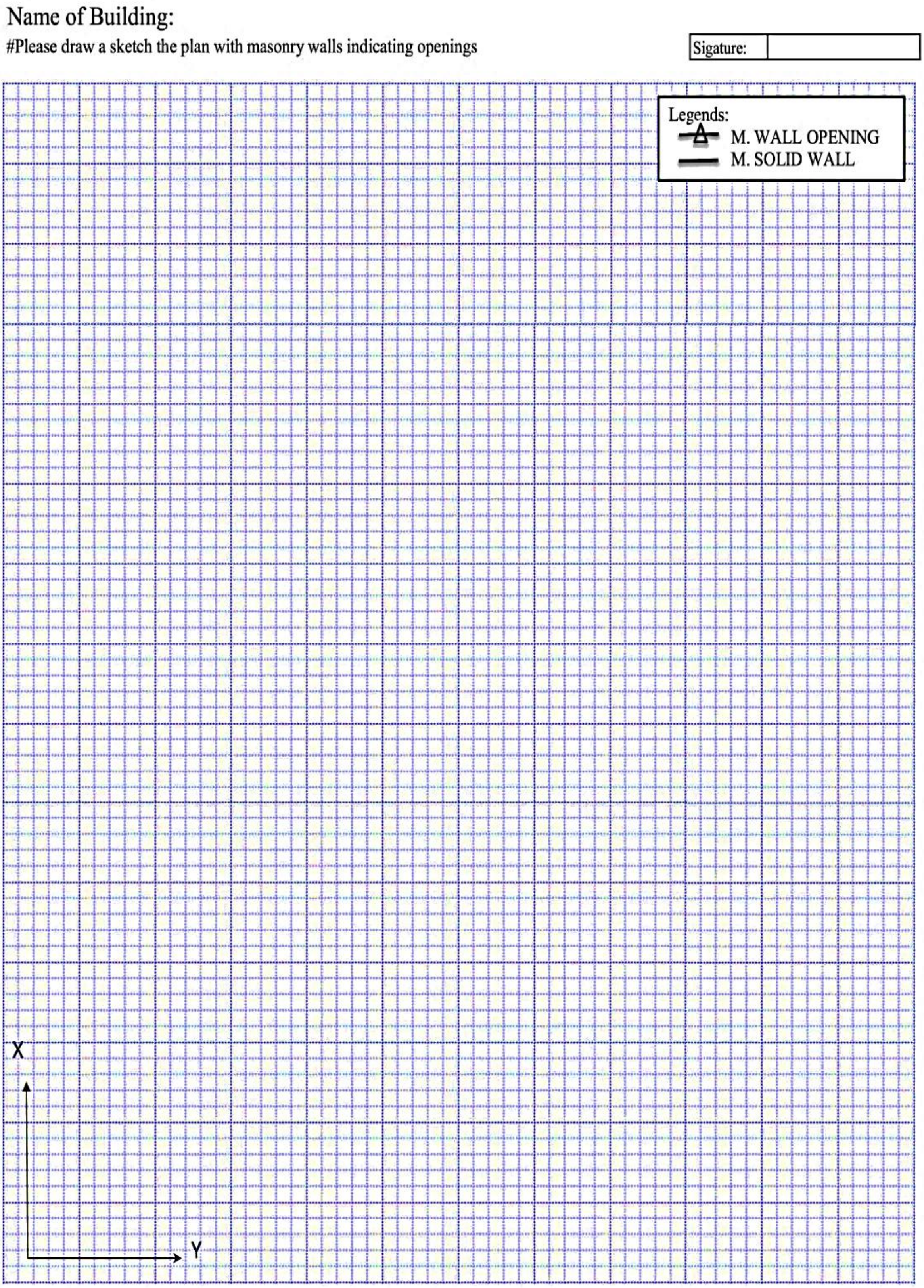
DIRECTION:

Address:

Please read carefully the selection criteria and put circle [○] in the appropriate items

No	Items	Selection Criteria	Please specify, If the value is found						Note
1	Categories	Floor/Roof System	RCC	Lime Steel/Joist Composite	Concerete Steel Composite	Wood Composite	Hybrid Composite	Others	
2	No of storey *(n)*, Height *(H)*, (m)		*Put story number & height*			*n=*	*,H=*		
3	Average wall span length (l_s), (m)		$l_1=$, $l_2=$, $l_3=$						
4	Average Opening Area, *(O)* (mm^2)		$O_1=$, $O_2=$, $O_3=$						
5	Average Thickness, *(t)* (mm)		$t_1=$, $t_2=$, $t_3=$						
6	Total length of Building, *(L)*, (m)		$L_1=$, $L_2=$, $L_3=$						
7	Vertical irreguarity	Regular= No irregularity Irregular= Ground floor parking/Soft Storey/ Weak Storey					Regular	Irregular	
8	Horizontal & Mass irregularity	Regular= No irregularity Irregular= Irregular in Plan and Geomatric Shape					Regular	Irregular	
		Water Tank & Generator	Yes / No,			Location (Also indicate in plan):			
9	Deterioration	None= No deterioration Minor=Spolling, Damp, Efflorecene in Wall & Minor crack Severe= Major Crack (>=1/8") & Damage				None	Minor	Severe	
10	Year of construction	New= less than 15 years Middle=15~30 years Old= More than 30 years				New	Middle	Old	
11	Other Notes								

Fig. 3.5 Developed RSAM survey sheet.



Name of Building:

#Please draw a sketch the plan with masonry walls indicating openings

Sigature:	

Legends:

M. WALL OPENING

M. SOLID WALL

Fig. 3.6 Pad for freehand sketch of the building.

3.6.2 Parameters of RSAM Survey Sheet

It is instructed that the surveyor should complete the rough sketch of the building, especially indicating the load-bearing wall locations. This shall be done by visually observing the building and noting its number of stories and shape. During completion of the form, double writing should be avoided. If necessary, a fresh RSAM sheet can be used to input the parameters. If any special case appears, the surveyor shall mention it on the right side of the sheet on the column named "Note". In the following sub-sections, each parameter of the survey data sheet is discussed separately as follows.

a) Diaphragm System

Five different diaphragm systems are given in the survey sheet, such as reinforced cement concrete (RCC), lime steel/joist composite, concrete steel composite, wood composite, and hybrid composite roof systems. However, only the rigid diaphragm roof system should be considered in the RSAM method.

b) Number of stories (n)

The number of stories is directly related to the total building weight. The surveyor will input the current total story number. If a building has a different story number or setback, the surveyor will use the maximum story number, excluding the "Chilekotha". However, the surveyor must mark the part and story number in the rough sketch of the RSAM survey sheet accordingly.

c) Number of spans (l_i)

One segment of an integrated load-bearing wall can be considered as a single span. Opening area in each load-bearing wall segment should be duly considered.

d) Average span length of walls (l_s)

Average span length is only applicable when walls are very uneven, but the dimension is closer. It is also challenging to measure floor area by visual inspection within a short time. Because it requires as-built drawing preparation, if architectural drawings are not available, this takes longer for the building survey. However, the following method considers the average span length (ls) of the building in both directions to overcome the limitation. The square of average span length (l_s) is the most straightforward way to approximately estimate the floor area of a building in a short time. Generally, the span length is not equal in each direction, and the number of spans is not the same. In this context, the investigator should check and measure one or two spans in both directions (longitudinal and transverse direction) of a building. Then the appropriate value for average span length is chosen based on engineering judgment. Figure 3.7 also shows an example of the inspection procedure of the average span length (l_s) of a surveyed building.

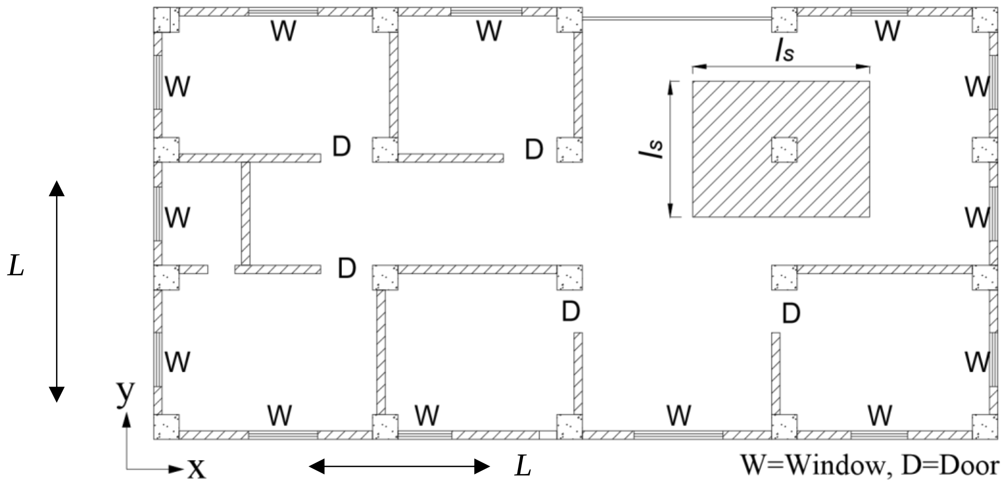


Fig. 3.7 Schematic floor plan of a building with average span length.

e) Average height of walls (H)

Typically, it is measured in the ground, considering the clear height from floor to roof beneath, using a measuring tape or a measuring laser meter. In case of different variations in heights in other storeys, it must be noted so that the numerical average can be done during calculations.

f) Average thickness of walls (t)

The thickness of exterior and interior walls of the building is measured individually for further calculation, and any thickness variations can be adjusted by taking a numerical average. However, only URM load-bearing walls with a thickness of 250 mm or more will be considered for seismic evaluation in this method.

g) Opening area of walls (OP)

The effect of opening on the stiffness and strength of URM walls is considered using a modification factor (F_{OP}) (Section 3.4.1, Chapter 3). The size of openings in URM load-bearing walls should only be calculated appropriately.

h) Vertical irregularity

Any irregularity due to discontinuity and abrupt changes in the URM load-bearing walls from the top to the ground floor should be properly checked and noted. For details of vertical irregularities of seismic resisting structures, the reader can refer to BNBC (2020).

i) Horizontal and mass irregularity

Any irregularity due to a change of geometric shapes (such as L, T, and U, etc.), floor mass, and location of URM load-bearing walls should be carefully checked and noted. For details of vertical irregularities of seismic resisting structures, the reader can refer to BNBC (2020).

j) Age of construction

The building year of construction, i.e., building age, reflects the quality of construction, concrete strength, as well as the design procedure adopted for a particular building. Therefore, building age affects its overall seismic capacity. The approximate age of a building can also indicate the possible structure type. The ability to identify the age of a building by considering its architectural style and construction materials requires an extensive knowledge of architectural history and past construction practice. In case of phased construction, the starting time of the first phase shall be taken into consideration.

k) Sketch of Floor Plan

A preliminary freehand sketch of the floor plan should be drawn at the bottom of the RSAM survey sheet. The primary purpose of this rough sketch is to have a preliminary idea about the floor plan and spatial arrangement of load-bearing walls. The surveyor should sketch the plan as clearly as possible for future reference.

3.4 Inspection procedure

Visual rating of buildings is basically intended for rapid assessment of large building stocks. So, a detailed inspection of all buildings in a stock may not be required. Simple measuring instruments, such as steel tape, scale, and laser meter, shall be used to determine the parameters. The surveyor should strive to obtain the most accurate values of the parameters. RSAM Index calculation requires parametric data for all floors; however, inspecting the ground and first floors, especially in inaccessible areas, is a considerable task. Parameters like wall span length, opening criteria, thickness, and height of the walls indicate the values from the ground floor only. The reason behind this is that the ground floor is typically the most vulnerable to seismic incidents. However, to understand the URM structural system, the possibility of a soft story, and any other vertical/horizontal irregularity or technical reasons necessary to fill out the RSAM survey form, the surveyor may survey other floors as well. The surveyor should take the required action to ensure entry at all crucial locations for the survey of the building. For this reason, he/she might provide the schedule 2/3 days before the inspection. If the surveyor cannot take some parameter due to any restriction, he/she will note other data, but not complete the survey. Irrational assumptions without confirmation are not encouraged. The surveyor should be capable of understanding the whole picture of the ground floor. If there is a possibility of a profound pounding effect, deterioration & structural cracks, the surveyor might include this information in the survey sheet under “Notes” as well.

3.4.1 Guidelines for Filling Out the Survey Data Sheet

In this section, the procedure for filling out the survey datasheet is discussed step by step.

Step 1: General Information

a) The surveyor will input the survey date, survey building name, and building address at the top of the survey data sheet as shown in Table 3.6.
b) The surveyor will write his name in the place of the Investigator located at the bottom of the sheet as shown in Table 3.7.
c) If possible, the surveyor will collect structural/architectural drawings of the building.
   However, if drawing is not available, it will not affect the survey.

Table 3.6 General information about the survey data sheet.

RSAM Survey Sheet
Name of the building: Date:
Address:

Table 3.7 Investigator's name in survey datasheet.

Name of the Investigator	Mr./Ms. X

Step 2: Floor System & Number of Stories
The surveyor will count the story number from outside the building. He/she will also write the category of the building, i.e., for which purpose the building is currently used, like residential/official/educational/institutional, etc., as shown in Figure 3.8.

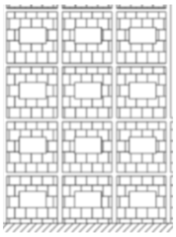
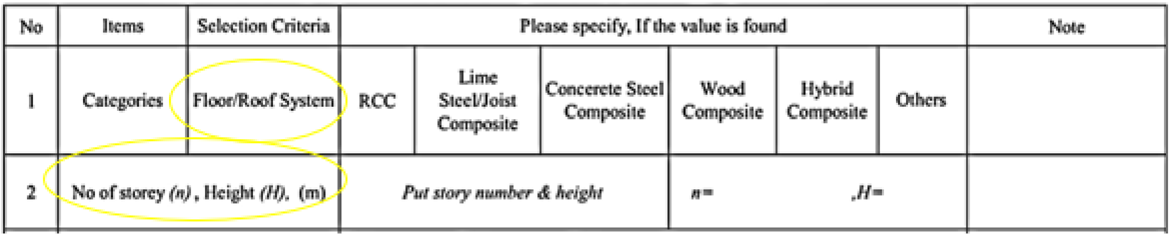


Fig. 3.8 Front view of the building showing the number of storeys.

Here, the illustration in Figure 3.8 shows the front view of the building. There is a difference in the number of stories in the same building. In this case, the most significant number should be used for surveys, and a note shall be kept for this story difference with a rough sketch. Table 3.8 presents an overview of building categories, the number of stories, and other relevant information collected in the survey datasheet. It categorizes structures based on their type, height, and construction details, providing a comprehensive dataset for analysis. This tabulation is crucial for assessing the seismic vulnerability of various building types across the study area.

Table 3.8 Building category, number of stories, and other information in the survey datasheet.



No	Items	Selection Criteria	Please specify, If the value is found						Note
1	Categories	Floor/Roof System	RCC	Lime Steel/Joist Composite	Concerete Steel Composite	Wood Composite	Hybrid Composite	Others	
2	No of storey (n), Height (H), (m)		*Put story number & height*			$n=$	$,H=$		

Step 3: Drawing a Rough Sketch of the building
The surveyor will draw a rough sketch of the building. In this sketch, the location of walls with their opening (with windows, doors, ventilators, etc.) should be drawn. The rough sketch should be as neat as possible in Figure 3.9.

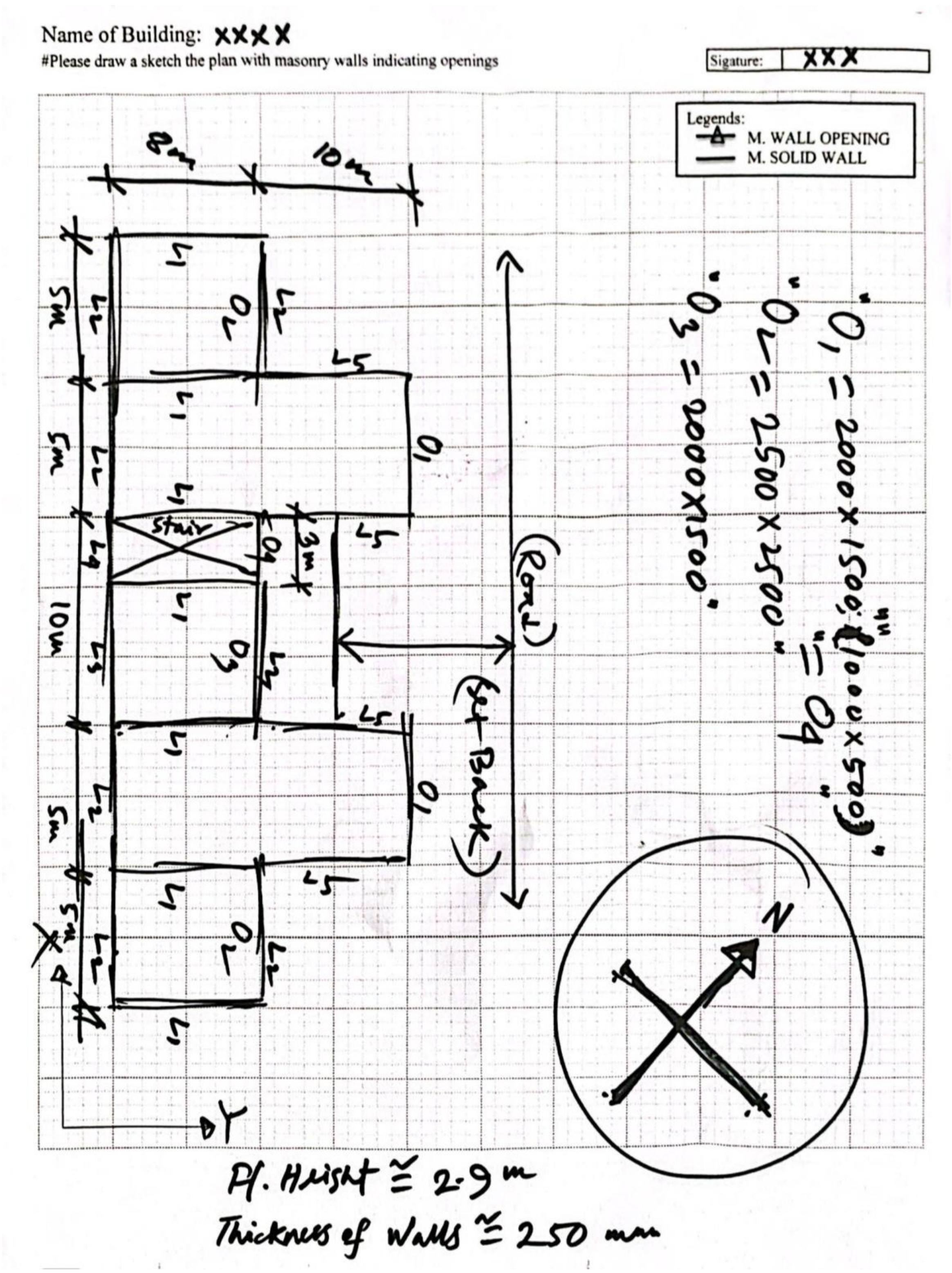


Fig. 3.9 On-site rough sketch of the building segment showing masonry walls with and without an opening sample.

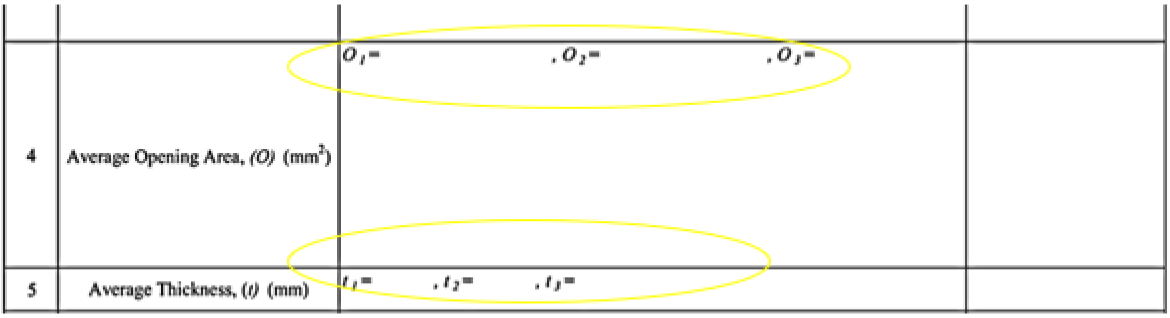
Step 4: Span Length

The surveyor should carefully determine the span length of each wall in each principal direction and indicate the same in the data sheet. Identification of URM walls is shown in Figure 3.7 previously.

Step 5: Masonry Wall Opening & Thickness

A wall opening in a single span, such as a window or door, should be considered. The total length and height of the opening should be appropriately taken. The thickness of each wall should be presented in Table 3.9.

Table 3.9 Masonry wall opening area in the survey data sheet.

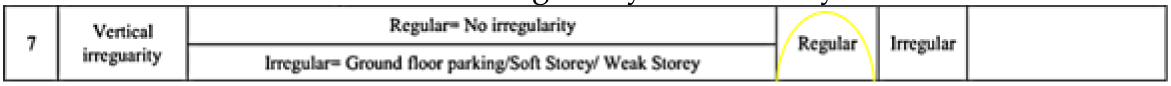


4	Average Opening Area, *(O)* (mm^2)	O_1= , O_2= , O_3=	
5	Average Thickness, *(t)* (mm)	t_1= , t_2= , t_3=	

Step 6: Vertical Irregularity

The surveyor should properly indicate if there is any vertical irregularity in the building. Suppose the surveyor cannot determine vertical irregularity on his/her own. In that case, they should draw rough sketches of the building, showing necessary elevations, so that the higher supervising authority can judge the building frame system. The surveyor should tick or encircle the case that best fits the building in Table 3.10.

Table 3.10 Vertical irregularity in the survey datasheet

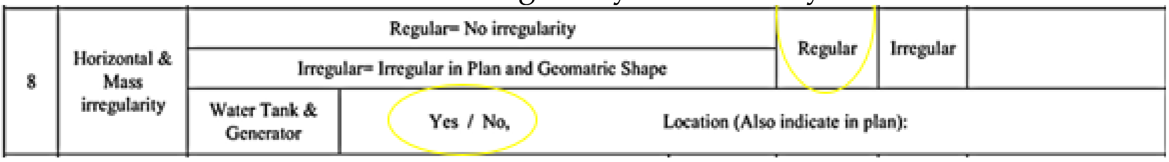


7	Vertical irreguarity	Regular= No irregularity	[✓ Regular]	Irregular	
		Irregular= Ground floor parking/Soft Storey/ Weak Storey			

Step 7: Horizontal Irregularity

Surveyors should properly indicate if there is any horizontal irregularity in the building. Suppose the surveyor cannot determine horizontal irregularity on their own. In that case, they should draw rough sketches of the building, showing the necessary plan and projection of the building, so that the higher supervising authority can judge the building frame system. The surveyor should tick or encircle the case that best fits the building in Table 3.11.

Table 3.11 Horizontal irregularity in the survey datasheet.

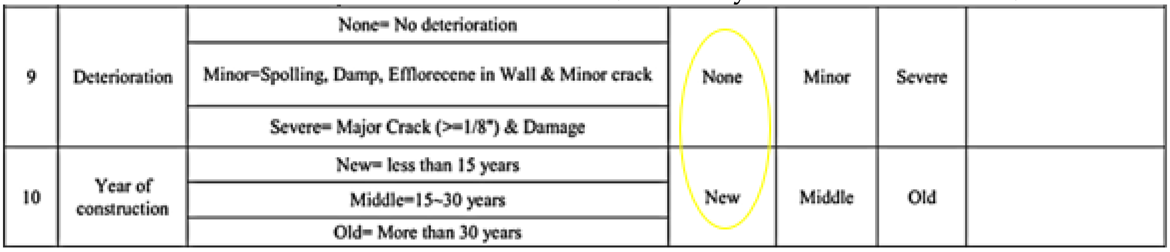


8	Horizontal & Mass irregularity	Regular= No irregularity	[✓ Regular]	Irregular	
		Irregular= Irregular in Plan and Geomatric Shape			
		Water Tank & Generator	Yes / No,	Location (Also indicate in plan):	

Step 8: Deterioration and Year of Construction

Judgment of deterioration is sometimes very crucial. It takes extensive knowledge and vast experience to understand whether the decline is structural or non-structural. For any confusion, the surveyor shall take photos of the damaged location for a better understanding of his/her supervising authority. Similarly, for years, construction surveyors have looked at the drawing and construction time. If the drawing of the building is not available, the surveyor may take information from the owner. If that is also not possible, he/she shall take as many pictures as possible to understand the architectural pattern and construction practice and notify his/her supervising authority. However, the precise year of construction is not a must, as the range is given in the datasheet. In the survey datasheet, items 9 and 10 represent the deterioration, F_D, and Year of Construction F_T. The surveyor should tick or encircle the case which best fits the building as shown in Table 3.12. Figures 3.10 and 3.11 show the site data collection consideration scenarios.

Table 3.12 Deterioration of concrete, F_d and year of construction, F_T.



9	Deterioration	None= No deterioration Minor=Spolling, Damp, Efflorecene in Wall & Minor crack Severe= Major Crack (>=1/8") & Damage	[✓ None]	Minor	Severe	
10	Year of construction	New= less than 15 years Middle=15~30 years Old= More than 30 years	[✓ New]	Middle	Old	

Fig. 3.10 Crack scaling during field survey.

Fig. 3.11 Condition of the URM building’s slab beneath.

CHAPTER 4: METHOD ADEQUACY AND PRIORITY SETTING

4.1 General

The adequacy of the RSAM method for assessing seismic vulnerability in unreinforced masonry (URM) buildings has been rigorously validated through experiments simulating real-world seismic conditions. These tests confirm the accuracy of the methodology for structural behavior prediction under seismic stress and its applicability to implementation. Moreover, a complete system of judgment criteria has been developed to help engineers rank buildings for detailed examination. Because of the heterogeneity of seismic risk over areas and the limited empirical data that exist, these criteria also involve factors such as structural stability, historical seismic behavior, and local seismic activity. Derived from CNCRP recommendations and formulated through analytical modeling, the requirements represent a well-organized and realistic vehicle for seismic risk assessment. To facilitate application, detailed thresholds and parameters suited to seismic zones, varying from age to materials, occupancy, and expected ground motion, are established, while inviting conformity and consistency with current safety standards, and optimizing capacity for future earthquakes.

4.2 Experimental Evaluation of the RSAM Method

The adequacy and robustness of the suggested approach are thoroughly validated through an extensive series of experiments conducted on unreinforced masonry (URM) walls. The tests are meticulously designed to replicate the real conditions to which URM buildings would be subjected during seismic activity, thereby facilitating an exhaustive validation of the proposed method. The results of the experiment, systematically tabulated in Table 4.1 and graphically presented in Figure 4.1, serve as a valuable benchmark for establishing the method's accuracy and reliability under consideration. The tests employ 1/3 reduced-scale samples of URM walls to replicate the behavior of full-scale structures, even though the size of the brick could not be scaled due to its brittleness. The RSAM survey sheet is a handy way to check how well existing brick buildings can handle earthquakes quickly. It helps inspectors gather key details, such as the building's construction, materials, and potential weaknesses, for each side of the building. The samples we test are designed to resemble real brick buildings in terms of materials, sizes, and construction methods. This way, the tests are as close to real-world situations as possible. To make things even more realistic, we push the brick samples sideways in a special frame that lets us control the force we apply. A hydraulic jack is used to move sideways, like how an earthquake would occur. This jack lets us apply force precisely and constantly. We can then watch closely how the brick walls act under different pressures. Along with the sideways push, we also put constant vertical pressure on the brick samples. This pressure is like the weight the wall would usually carry from the building above and other items on it. By keeping this pressure steady, our tests better show how sideways and vertical forces interact in a real building. Adding this vertical pressure is a key part of our testing because it significantly alters how the brick walls behave. It can change how the walls break, their strength, and how much they can hold. So, by adding it to the test, the results should provide a more accurate picture of how real brick buildings will behave during an earthquake. During the tests, we gathered a lot of information, including how cracks grow in the brick walls. We maintain meticulous records and compare them to assess the predictive accuracy of our method for how brick walls will behave under pressure. Table 4.1 presents the test results, providing insight into the accuracy of our process, its strengths, and areas for improvement. Figure 4.1 adds to this data by showing graphs and pictures of the brick walls before and after the tests. It also shows diagrams of the crack patterns that appeared during the tests. Figure 4.1 is used to provide a more complete picture of the performance of the URM walls and the effectiveness of the methodology developed.

Table 4.1 URM Specimens experiment details.

Panel ID	Size (Lxh) & Opening mm x mm	Aspect Ratio (h/L)	Mortar Strength f'_c (MPa)
URMP1	1500 x 1000	0.66	9.5
URMP2	1500 x 1000 (400x400)	0.66	9.5
Panel ID	Axial Load (kN)	Lateral Load Capacity (kN)	Failure Mode
URMP1	31	47.1	Sliding Bed-Joint
URMP2	31	36.3	Diagonal Tension & Bed-Joint

The results in Table 4.1 provide a general summary of the structural performance of unreinforced masonry (URM) panels in experimental environments, illustrating the dominant effect of design factors such as aspect ratio, mortar strength, axial load, and presence of openings on their seismic sustainability. URMP1 and URMP2 share the same 9.5 MPa mortar strength and the same aspect ratio of 0.66 but are tested axially under 31 kN to replicate actual vertical loads in actual structures. The only difference between them in the case of carrying lateral load is the inclusion of a 400 mm x 400 mm opening within URMP2. URMP1 without an opening achieves a lateral load of 47.1 kN and fails primarily in sliding along the bed-joint, which is a mode of failure common in panels of lower aspect ratios governed by shear stresses. But URMP2, because of the opening, is weaker. It can only handle a 36.3 kN lateral load. Also, it fails in a more complicated way, with both diagonal tension and bed-joint sliding. This shows that the opening causes stress to build up and makes the structure less sound. These findings underscore the instrumental role that openings play in undermining the seismic integrity of URM walls with concomitant loss of load capacity and more complex failure mechanisms. The results emphasize the need to incorporate such variables into seismic analysis and retrofitting designs to ensure the security and durability of URM buildings, particularly those situated in seismically exposed regions. The understanding of the interaction between these parameters will enable engineers to design more effective methods of analysis and enhancement of URM building seismic performance, ultimately providing safer construction procedures in seismically active regions.

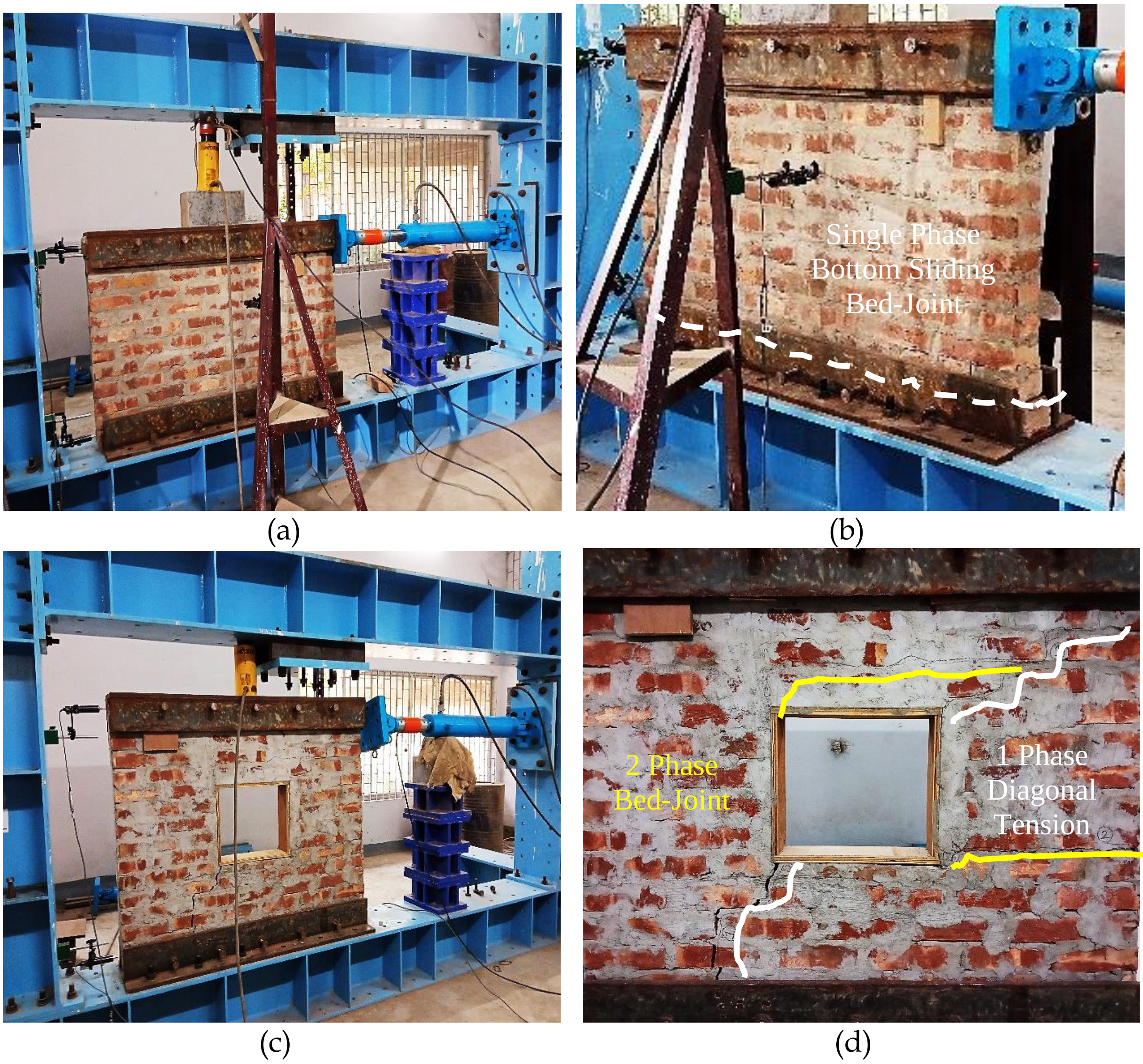


Fig. 4.1 The experimental setups are visible at (a) and (c), the failure modes are identifiable in (b) and (d), respectively for URMP1 and URMP2.

Overall, the incorporation of lateral load, axial load, and extensive data collection creates a solid experimental foundation for confirming the recommended method. The extensive validation procedure ensures that the predictions of the process are not only theoretically sound but also applicable in actual URM buildings. The outcome of such experiments increases the reliability of the created method. It demonstrates its ability to successfully assess the seismic performance of URM walls, in addition to contributing to the overall field of earthquake engineering.

4.3 Review and Comparative Data Analysis of URM Experiments

To accurately evaluate the developed method, a complete set of experimental data on 25 masonry wall specimens, including special ones URMP1 and URMP2, was considered. To see how the walls would react during an earthquake, we put them through different stress tests. What's cool is that 23 of these tests came from FEMA 307 (1998). This report is significant because it provides extensive information on how old brick buildings behave when shaken. Using this info means our study is based on solid, real-world tests, making it way more trustworthy. The FEMA 307 tests, along with the

URMP1 and URMP2 stuff, give us a good way to see how strong the walls are. We looked at lateral strength. It's crucial for understanding how well brick walls can withstand earthquakes. We checked it using the Rapid Seismic Assessment Method (RSAM). This helps estimate how strong the walls are based on factors like their size, material, and loading. Figure 4.2 shows how the RSAM estimates match up with the test results. The diagram has four parts: (a) a simple comparison of the RSAM guesses and the actual strength, (b) a graph showing how close the predicted load is to the real load, (c) a check to see how much the predictions vary, and (d) a curve showing how likely the RSAM predictions are to be safe for different thresholds. These analyses provide a quantitative basis for evaluating the conservatism and reliability of the RSAM used in seismic vulnerability studies.

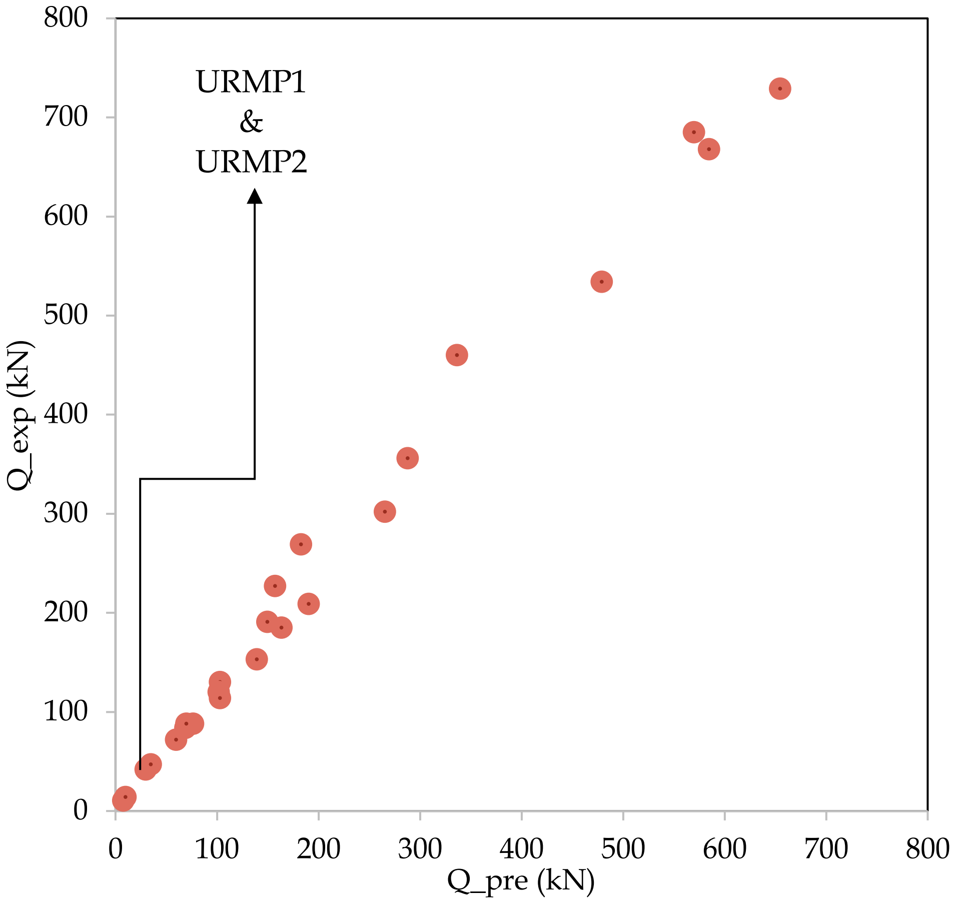


Fig. 4.2 (a) Lateral strength of URM walls as obtained from the RSAM method and experiments.

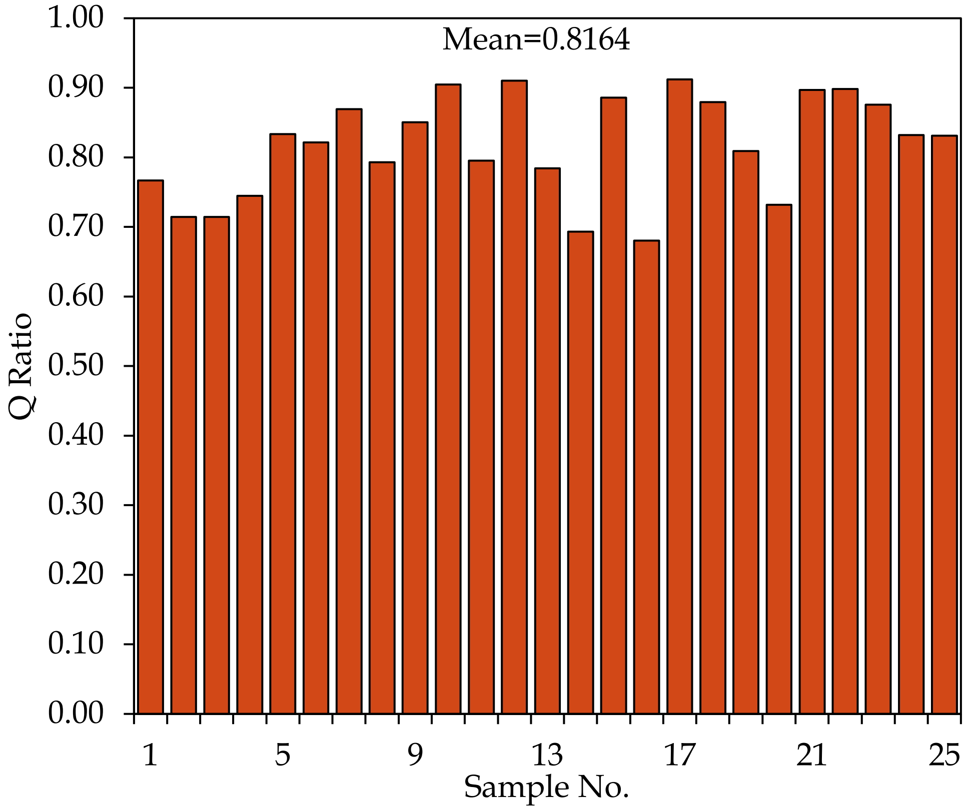


Fig. 4.2 (b) Distribution of the predicted-to-experimental load ratios (Q_pre/Q_exp).

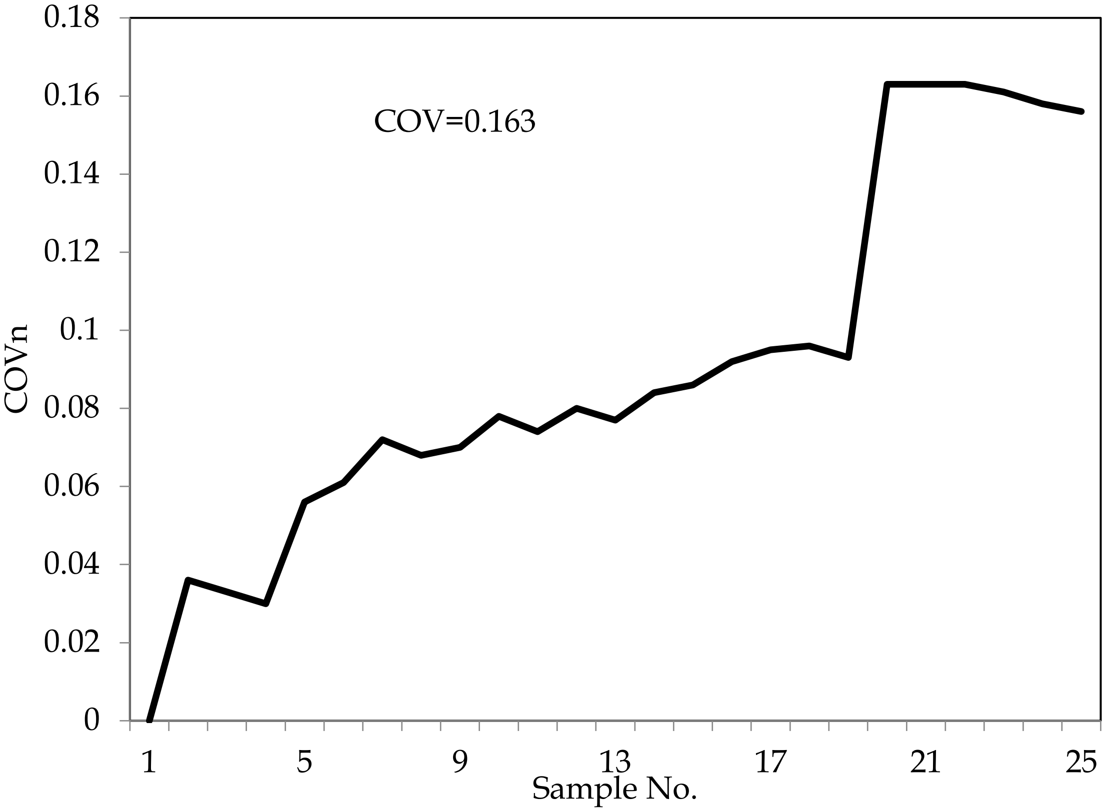


Fig. 4.2 (c) Coefficient of variation (COV).

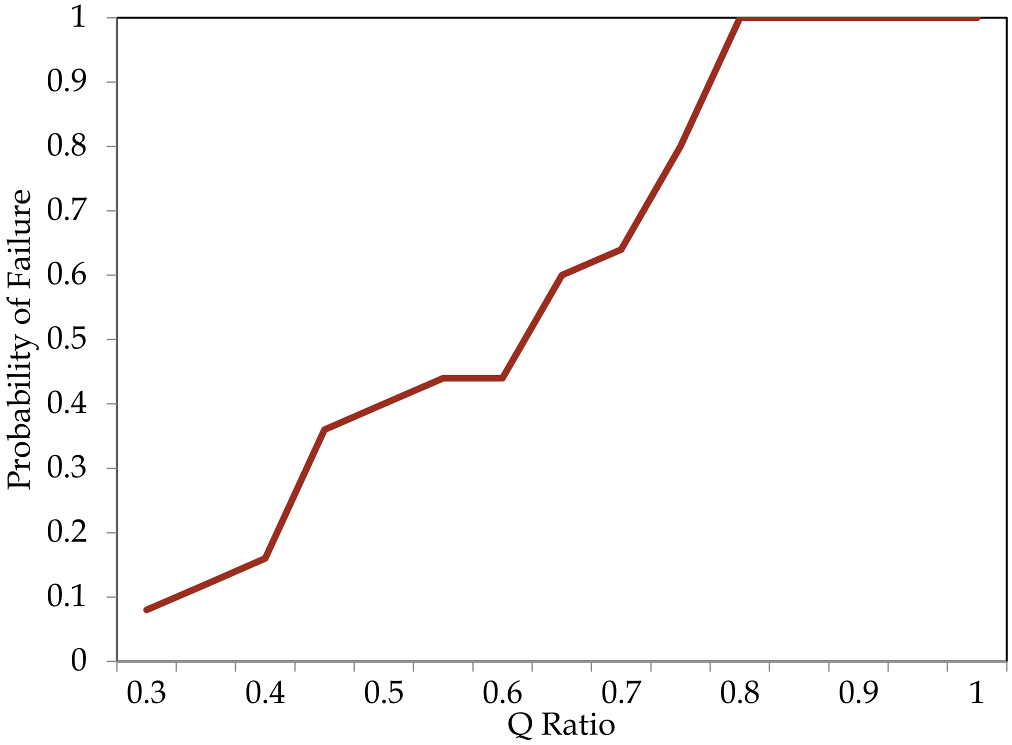


Fig. 4. 2 (d) Fragility curve for the analysis.

The comparison reveals the RSAM-predicted capacities to be consistently lower than the experimental ones. The outcome highlights the conservatism of the VRM predictions, which is highly desirable for the preliminary seismic vulnerability assessment of existing unreinforced masonry (URM) buildings. Statistically, the average ratio of the predicted to experimental lateral load capacities (Q_pre/Q_exp) is computed to be approximately 0.8164, with a coefficient of variance of roughly 0.163. These values exhibit a moderate degree of variation but establish that the RSAM does not overestimate wall capacity. This conservatism inherently works in favor of structural safety, and any seismic deficiencies are unlikely to be conservatively estimated in the assessment.

4.4 Judgement of Priority Setting

In seismic design, it is essential to have a firm set of judgment criteria for guiding engineers in making decisions on construction priorities for a comprehensive seismic appraisal. With a lack of empirical damage data of unreinforced masonry (URM) buildings all over the globe, these criteria provide a structured method of decision-making, especially with respect to resource and time factors. The requirements have been established with caution using experiences gained from the visual assessment methods and improved by analytical results of multi-storey URM building models, all as required in the CNCRP guidelines for seismic safety evaluation (CNCRP, 2015). Thus, the criteria are not only handy but also based on known safety protocols. The factors influencing decisions comprise a broad array of items, such as structural integrity, seismic history in the past, and probable impacts of future earthquakes. The items are crucial in assessing relative risk for each building, allowing engineers to assign top priority to the most seismically vulnerable buildings. Additionally, the criteria are framed to take into consideration regional variations in seismicity, given that URM buildings in different seismic zones can be subjected to varying levels of risk. To facilitate the practical application of the criteria, Table 4.4 categorizes the degree of judgment for URM buildings in terms of four seismic zones with definite parameters and thresholds required for seismic safety assessment. These parameters include building age, construction materials, building height, occupation type, and ground motion expected per zone. With these detailed guidelines, engineers can ensure that their assessment is not only objective and uniform but also in line with up-to-date seismic safety practice, thus creating a more seismic risk-resilient built environment.

4.5 Analytical Background of Judgement Criteria Setting

Seismic and structural safety of a building can be determined by the following Equation 4.1, which balances applied loads with available structural component strength and resistance (BRI, 2001).

$$I_s \geq I_{s0} \qquad (4.1)$$

I_sThe seismic index of URM buildings and I_{s0} is the seismic demand index of the URM buildings. If the above equation is satisfied, then the building can be assessed to be "Safe". Otherwise, the building should be evaluated to be "Uncertain" for seismic safety, as described in the CNCRP manual developed by PWD, 2015. Seismic demand index I_{s0}Must be set to meet the seismic capacity as required by the Bangladesh National Building Code (BNBC, 2020). Equation 4.2 can be used to calculate the seismic demand index, I_{s0} as

$$I_{s0} = \frac{2}{3} \times Z \times I \times C_s \qquad (4.2)$$

Z is the seismic zone coefficient, *I* is the structural importance, and Cs is the normalized acceleration spectrum, which is a function of building period and soil classes (Site Class) (BNBC, 2020). Site class "D" is considered for judgment criteria fixing. Figure 4.3 demonstrates the existing seismic zones in Bangladesh, which are deemed to standardize the level of judgment's numerical range where RSAM is compared with I_{s0}.

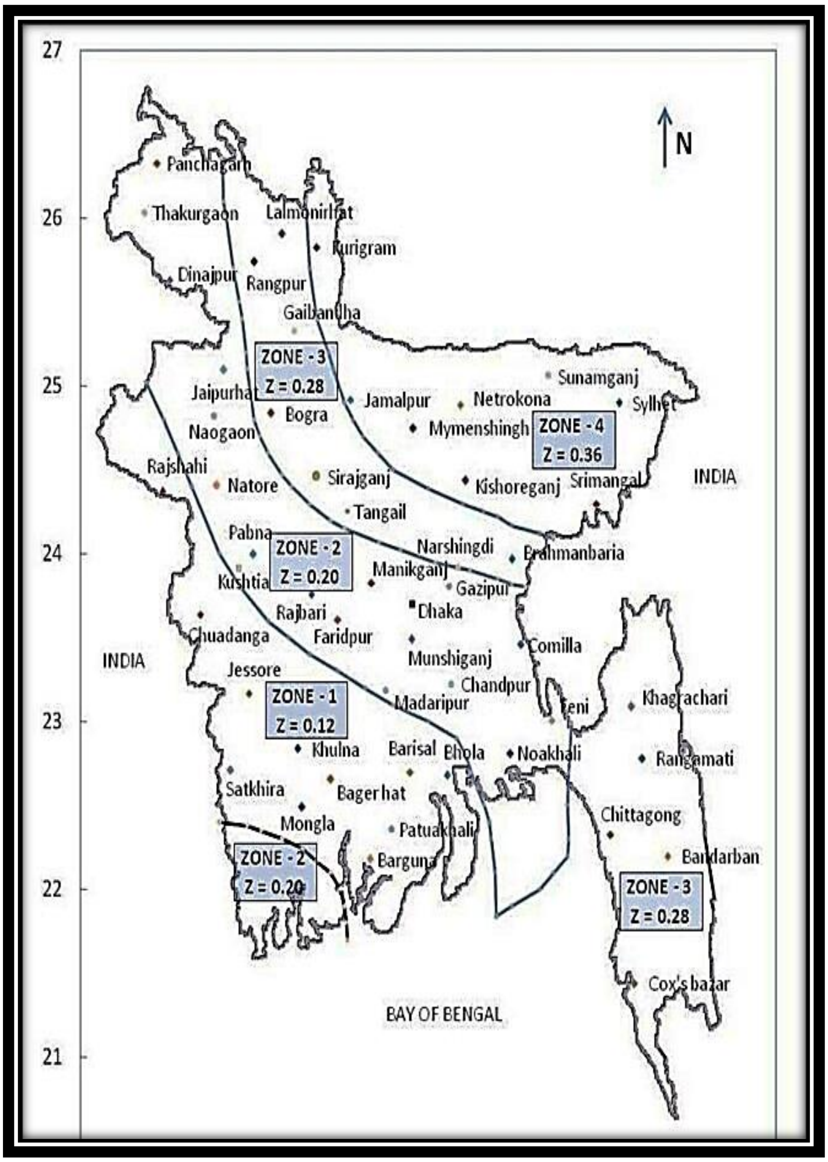


Fig. 4. 3 Seismic zone map, BNBC 2020.

4.6 Levels of Judgement

In this context, a comprehensive set of judgment criteria has been meticulously developed to assist professional engineers in making informed decisions regarding the prioritization of buildings for detailed seismic evaluation. These requirements are crucial as they allow engineers to assess which buildings must be given a higher level of priority relative to others, particularly when time and available resources are scarce. These requirements are justified by the fact that adequate damage data for unreinforced masonry (URM) buildings are not always available for all areas. Therefore, it is challenging to make decisions by empirical approaches alone. To bridge this lack, the criteria for judgment of seismic priority for URM buildings have been highly developed based on the output of a rapid assessment method, which has also been further upgraded based on analytical results from multi-storey URM building models. These models have been extensively analyzed with the CNCRP guideline for the judgment of seismic safety (CNCRP, 2015) as a reference, so that the criteria will be highly based on current safety practice.

The selection factors address a wide range of issues, including stability of structure, historic seismic performance during earlier earthquakes, and probability of impact by future earthquakes. All the said factors are utilized to determine relative risks associated with each structure so that engineers can identify buildings with the highest potential for seismic damage. The guidelines change a bit depending on where you are. Buildings in different earthquake zones have different dangers. Table 4.2 groups earthquake zones and shows how to judge older brick buildings. It provides a basic overview of what to consider when assessing the safety of these buildings during earthquakes. Some of these parameters include, but are not limited to, building age, building material in construction, building height, type of occupation, and the anticipated ground motion per seismic zone. By adhering to these guidelines, the engineers can make their estimates consistent, impartial, and in accordance with the latest seismic safety standards, hence making the whole built environment seismically resilient.

Table 4.2 Level of judgment in prioritizing building settings based on I_{RS}. (Bhuiyan & Islam, 2022).

Level of Judgment	Range of I_{RS}			
	Low Seismic Zone	Moderate Seismic Zone	High Seismic Zone	Critical Seismic Zone
Least priority	above 0.22	above 0.36	above 0.50	above 0.65
Low priority	0.15-0.22	0.28-0.36	0.28-0.50	0.28-0.65
Moderate priority	0.10-0.15	0.17-0.28	0.17-0.28	0.17-0.28
High priority	0.08-0.10	0.10-0.17	0.10-0.17	0.10-0.17
Highest priority	Less than 0.08	Less than 0.10	Less than 0.10	Less than 0.10

Let's proceed to the comparative analysis of the results presented in Table 4.2, showing the level of judgment of I_{RS} safety priority construction in various seismic zones.

a) Low Seismic Zone

In areas where earthquakes aren't as common, here's how we decide which buildings to check first:

- Lowest Priority: If a building has an I_{RS} above 0.22, it's safe and doesn't need checking right away.
- Low Priority: Buildings with an I_{RS} between 0.15 and 0.22 are relatively safe, so we don't need to rush to inspect them.
- Medium Priority: If the I_{RS} is between 0.10 and 0.15, the building should be looked at carefully since it might be risky.
- High Priority: Buildings with an I_{RS} between 0.08 and 0.10 need to be checked sooner rather than later to assess their earthquake resistance.

- Highest Priority: Any building with an I_{RS} below 0.08 requires immediate attention. These buildings are at the highest risk, even in areas with infrequent earthquakes, and may need strengthening.

b) Moderate Seismic Zone

In areas with a bigger earthquake risk, the priorities are stricter:

- Lowest Priority: Buildings with an I_{RS} of 0.36 or higher can handle moderate shaking well, so they're last on the list to check.
- Low Priority: An I_{RS} between 0.28 and 0.36 means the building is reasonably safe, but we should still check for any weak spots.
- Medium Priority: If the I_{RS} is between 0.17 and 0.28, we need to check these buildings more closely to figure out how safe they are if the ground shakes.
- High Priority: Buildings with an I_{RS} between 0.10 and 0.17 need to be assessed quickly because they're more likely to get damaged in an earthquake.
- Highest Priority: Anything below 0.10 I_{RS} is a top priority. Because the earthquake risk is greater, these buildings could be in danger of falling and need to be dealt with right away.

c) High Seismic Zone

There is a more cautious prioritization required in high seismic zones with the risk of intense seismic activity.

- Least Priority: An I_{RS} of more than 0.50 is considered least priority. Though such buildings are relatively safe, regular checking is advised, considering the higher risk in these areas.
- Low Priority: A low priority is reflected in an I_{RS} of 0.28 to 0.50. These buildings present a slightly greater risk and need to be inspected regularly.
- Medium Priority: Moderately vulnerable buildings with an I_{RS} of 0.17 to 0.28 are assigned medium priority. These buildings may need to be strengthened to improve seismic resistance.
- High Priority: Highly exposed buildings that have an I_{RS} of 0.10 to 0.17 are assigned high priority. Such buildings are to be inspected at the earliest.
- Highest Priority: Construction with an I_{RS} of < 0.10 has the highest priority. In a high seismic zone, these structures are most vulnerable to seismic forces and thus require urgent intervention to prevent damage.

d) Critical Seismic Zone

In earthquake zones, here's how we rank buildings for safety checks from least to most urgent:

- Lowest Priority: If a building's I_{RS} is above 0.65, it's the lowest priority. It should be able to withstand a major quake.
- Low Priority: Buildings with an I_{RS} between 0.28 and 0.65 are a low priority. They're stable, but we still need to check them regularly for earthquake risks.
- Medium Priority: An I_{RS} of 0.17 to 0.28 means a building is medium priority. It's somewhat at risk, so we should check it out and maybe reinforce it.
- High: Buildings with an I_{RS} of 0.10 to 0.17 are high priority. They're at high risk and need immediate inspection and possible repairs.

- Highest Priority: Any building with an I_{RS} below 0.10 in a central earthquake zone is a top priority.

These buildings could collapse in a quake, so they need fixing ASAP. Table 4.2 helps engineers grade buildings for earthquake safety. The I_{RS} considers different shaking intensity levels and provides extra care to dangerous buildings. By using these grades, engineers can spend money smartly, focusing on buildings that are most likely to cause injuries or collapse during a quake. This not only makes cities stronger but also helps use resources wisely when it comes to reducing earthquake risks.

CHAPTER 5: APPLICATION OF RAPID SEISMIC ASSESSMENT METHOD (RSAM)

5.1 General

This chapter explores the application of the Rapid Seismic Assessment Method (RSAM) on a simple, two-story brick house to determine its earthquake resilience. We're using a 40-year-old house as an example. It's located in an area prone to earthquakes and has relatively soft ground. To do this, we're looking at things like how long and thick the walls are, where the openings are, and how strong the mortar is between the bricks. The house is in decent condition, with some wear and tear, but no significant cracks or anything unusual. All of this helps us determine its Rapid Seismic Index (I_{RS}), which indicates how likely it is to be damaged in a quake. Through systematic application of this building to the proposed Method, we attempt to determine the seismic resilience of the building and the interventions or retrofitting necessary. This method provides a primary first-line assessment that assists in the prioritization of buildings for subsequent examination, eventually resulting in improved earthquake preparedness and safety. This chapter also made the numerical simulation and verification of the application phenomena, comparing with a detailed evaluation.

5.2 Rapid Seismic Index I_{RS} Calculation

Calculation of the Rapid Seismic Index I_{RS} at the ground floor of a 2-story URM residential building (Figure 5.1) using the properties given as follows:

Length of each wall segment, L_1, L_2, L_3, L_4, L_5, L_6 and L_7 = 4000 *mm*, thickness of each wall = 250 *mm*, D_1 =1000 x 2200 *mm* and W_1=1500 x1250 *mm.* This 40-year-old building is in a moderate seismic zone, with medium-soft ground conditions. The physical condition of the load-bearing walls of the building is moderate; no major cracks are found. No vertical/ horizontal irregularity is found. The bed-joint shear strength of the masonry panel τ_0Is 0.10 MPa. A typical floor plan of the building is shown in Figure 5.1. A full-in survey datasheet is given in Figure 5.2. From the information collected in the datasheet, the following calculations are done to determine the I_{RS} of the building.

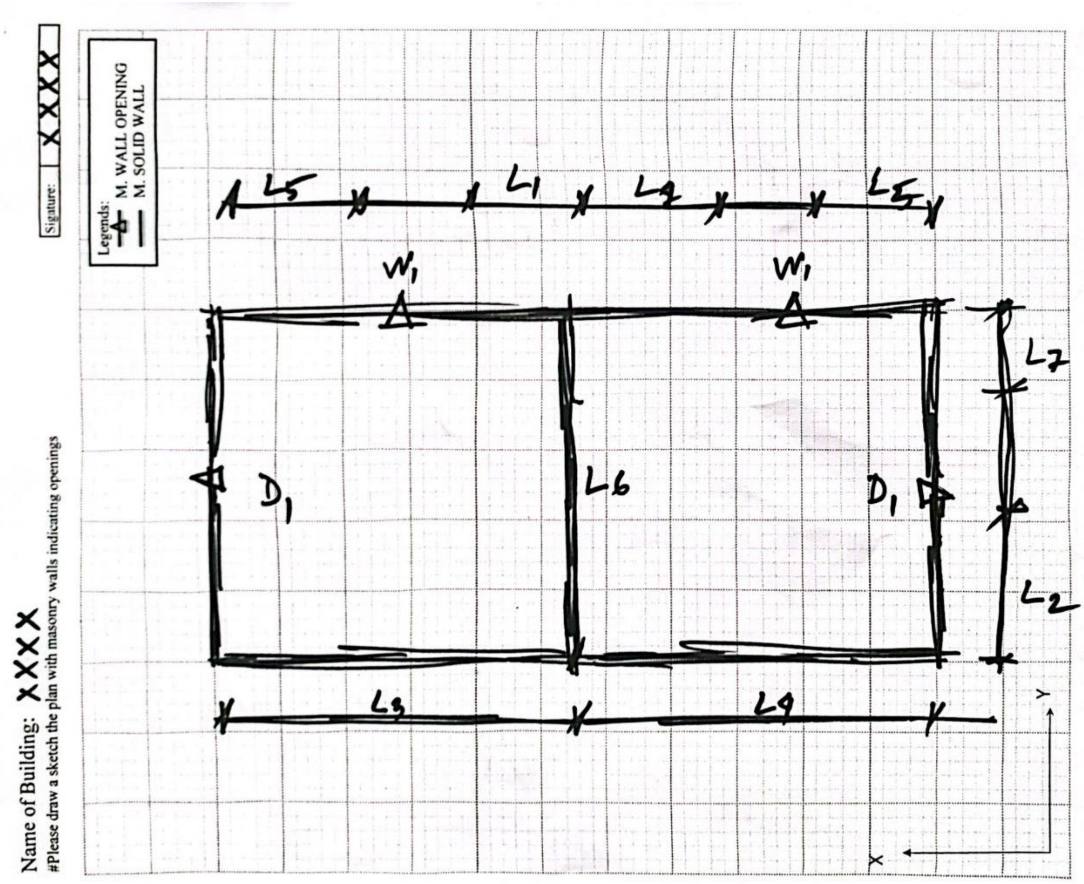
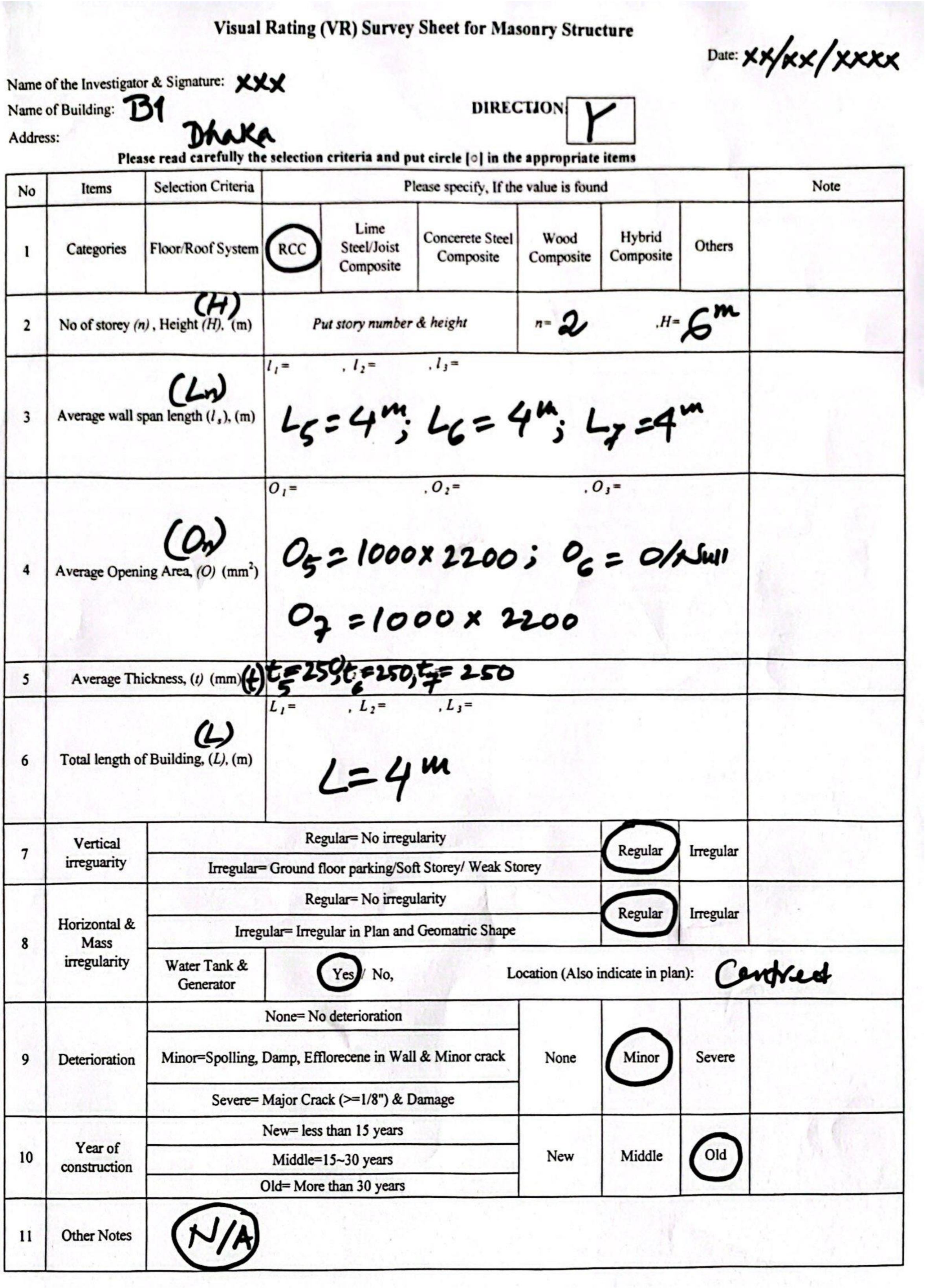


Fig. 5.1 On-site, sketched a partial floor plan of the 2-storey URM building.



Visual Rating (VR) Survey Sheet for Masonry Structure

Date: XX/XX/XXXX

Name of the Investigator & Signature: XXX

Name of Building: B1

DIRECTION: Y

Address: Dhaka

Please read carefully the selection criteria and put circle [○] in the appropriate items

No	Items	Selection Criteria	Please specify, If the value is found						Note
1	Categories	Floor/Roof System	[✓ RCC]	Lime Steel/Joist Composite	Concerete Steel Composite	Wood Composite	Hybrid Composite	Others	
2	No of storey *(n)*, Height *(H)*, (m) (H)		*Put story number & height*			$n=2$		$,H=6^m$	
3	(L_n) Average wall span length (l_s), (m)		$l_1=$, $l_2=$, $l_3=$ $L_5=4^m$; $L_6=4^m$; $L_7=4^m$						
4	(O_n) Average Opening Area, *(O)* (mm^2)		$O_1=$, $O_2=$, $O_3=$ $O_5=1000\times2200$; $O_6=0$/Swll $O_7=1000\times2200$						
5	Average Thickness, *(t)* (mm) (t)		$t_5=250$, $t_6=250$, $t_7=250$						
6	(L) Total length of Building, *(L)*, (m)		$L_1=$, $L_2=$, $L_3=$ $L=4^m$						
7	Vertical irreguarity	Regular= No irregularity Irregular= Ground floor parking/Soft Storey/ Weak Storey					[✓ Regular]	Irregular	
8	Horizontal & Mass irregularity	Regular= No irregularity Irregular= Irregular in Plan and Geomatric Shape					[✓ Regular]	Irregular	
		Water Tank & Generator	[✓ Yes]/ No,		Location (Also indicate in plan): Centred				
9	Deterioration	None= No deterioration Minor=Spolling, Damp, Efflorecene in Wall & Minor crack Severe= Major Crack (>=1/8") & Damage				None	[✓ Minor]	Severe	
10	Year of construction	New= less than 15 years Middle=15~30 years Old= More than 30 years				New	Middle	[✓ Old]	
11	Other Notes	N/A							

Fig. 5.2 On-site filled survey data.

Step 1: Calculation of the self-weight of the building

i) Weight calculation and assumptions are shown in Table 5.1.

Table 5.1 Weight of walls of the building (Unit weight of brick panel=16 kN/m³ and no. of floors is 2)

Wall Id	Length (m)	Height (m)	Opening area (m^2)	Thickness (m)	Weight (kN)
L1	4.0	3.0	1.2 x 1.0	0.250	81.0
L2	4.0	3.0	1.2 x 1.0	0.250	81.0
L3	4.0	3.0	0	0.250	96
L4	4.0	3.0	0	0.250	96
L5	4.0	3.0	1.5 x 2.1	0.250	78.4
L6	4.0	3.0	0	0.250	96
L7	4.0	3.0	1.5 x 2.1	0.250	78.4
Total weight of walls, W_w					606.8

ii) Weight of the RC floors of the building

Area of each floor = 8 x 4 =32 m^2, Number of floors = 2, Unit weight of concrete = 24 kN/m^3, and Thickness of RC slab =150 mm.

So, the weight of floors, W_s = 2 x 32 x 0.150 x 24 = 230.4 kN.

iii) Superimposed dead and live loads

Area of each floor = 8 x 4 =32 m^2, Number of floors = 2, Live load = 3.0 $kN/m^{2,}$ and Floor finish and other loads = 3.0 kN/m^2.

So, the weight of the superimposed dead load live load, W_{SL} = 2 x 32 x 6 = 384kN.

Total self-weight of the building, ΣW = 606.8 + 230.4 + 384 =1231.2 kN.

Step 2: Calculation of tributary force for each wall

Total weight of floor slabs, superimposed, and live load to be distributed among the walls = 230.4 + 384 = 614.4 kN. Total length of walls is 28 *m*. The tributary force in each wall is proportional to its length and tributary area, as shown in Table 5.2.

Table 5.2 Calculation chart of tributary force for each wall.

Wall Id	Length (m)	Weight (kN)	Tributary weight of floor loads (kN)	Compressive force applied to wall, P_{CE} (kN)	Compressive stress applied to wall, f_{ae} (MPa)
L1	4.0	81.0	87.8	168.8	0.17
L2	4.0	81.0	87.8	168.8	0.17
L3	4.0	96.0	87.8	183.8	0.18
L4	4.0	96.0	87.8	183.8	0.18
L5	4.0	78.4	87.8	166.2	0.17
L6	4.0	96.0	175.6	271.6	0.27
L7	4.0	78.4	87.8	166.2	0.17

Step 3: Calculation of shear strength for each wall (Table 5.3).

Table 5.3 Calculation chart of shear strength for each wall.

Wall Id	Compressive stress applied to wall, f_{ae} (MPa)	Shear strength, τ_{wi} (MPa) $(0.1+0.4f_{ae})$	X-area of wall, A_{wi} (mm^2) x10^6	Shear strength, Q_{mwi} (kN)
L1	0.17	0.170	1.00	169.67
L2	0.17	0.170	1.00	169.67
L3	0.18	0.174	1.00	173.51
L4	0.18	0.174	1.00	173.51
L5	0.17	0.163	1.00	163.43
L6	0.27	0.209	1.00	208.62
L7	0.17	0.163	1.00	163.43

Step-4: Calculation of modification factors for each wall.
The modification factor for each wall is estimated using the expression shown in the Table 5.4 & 5.5 below.

Table 5.4 The modification factors used for calculation.

Modification Factor	Weightage factor		
F_{OP}	F_{OP}=1-OP (%)/40, OP ≤ 40%; OP: Opening Area (%) of Wall		
F_{SR}	F_{SR} = 1.0: SR<9; F_{SR} = -0.0625xSR + 1.5625: 9≥ SR ≤ 25, F_{SR} = 0: SR > 25. SR: Slenderness Ratio of Wall;		
F_{AR}	F_{AR} = 0.8: AR< 0.5; AR: Aspect Ratio of Wall, F_{AR} = -0.367xAR + 0.9835: 0.5≤ AR ≤2.0, F_{AR} = 0.25, AR>2.0.		
F_D	Good	Minor (Moderate)	Severe
	1	0.75	0.6

Table 5.5 Considered, modification factors for calculation.

Wall Id	Aspect ratio (AR)	F_{AR}	Slenderness ratio (SR)	F_{SR}	Opening area (OP, %)	F_{OP}	Deterioration	F_D
L1	0.75	0.70	12	0.81	10	0.75	Minor	0.75
L2	0.75	0.70	12	0.81	10	0.75	Minor	0.75
L3	0.75	0.70	12	0.81	0	1	Minor	0.75
L4	0.75	0.70	12	0.81	0	1	Minor	0.75
L5	0.75	0.70	12	0.81	26.25	0.34	Minor	0.75
L6	0.75	0.70	12	0.81	0	1	Minor	0.75
L7	0.75	0.70	12	0.81	26.25	0.34	Minor	0.75

Step-5: Calculation of modification factors for the entire building (Table 5.6-5.8).

Table 5.6 Factors for geometric regularity, irregularity and building age.

Modification factor	Regular		Irregular
Vertical irregularity *(F_{IV})*	1		0.8
Horizontal irregularity *(F_{IH})*	1		0.9
Age of construction *(F_T)*	New(<15yrs)	Middle (15 to 30yrs)	Old (>30yrs)
	1	0.95	0.9

Factor	No Risk	Low-Level	Moderate-Level	Severe-Level
Pounding Effect (F_P)	1	0.95	0.9	0.75

Table 5.7 Considered factors for calculation include the ponding factor.

Modification factors	Condition	Weight age factor
Vertical Irregularity (F_{IV})	Regular	1.0
Horizontal Irregularity (F_{IH})	Regular	1.0
F_T	Old	0.9
F_P	N/A	1

Step-6: Calculation of the I_{RS} of the building in the Y direction.

Table 5.8 Final calculation chart for I_{RS}.

Wall Id	$I_{RSy} = \left[\sum_{i=1}^{n}\left(\frac{Q_i}{\sum W}.\ F_{OPi}.\ F_{SRi}.\ F_{ARi}.F_{Di}\right)\right].F_{IV}.F_{IH}.F_T.F_P$									
	$Q_i/\sum W$	F_{OPi}	F_{SRi}	F_{ARi}	F_{Di}	F_{IV}	F_{IH}	F_T	F_P	I_{RSy}
L5	0.13	0.75	0.81	0.70	0.75	1.0	1.0	0.9	1	0.12
L6	0.17	0.75	0.81	0.70	0.75					
L7	0.13	1.00	0.81	0.70	0.75					
$\sum_{i=1}^{n}\left(\frac{Q_i}{\sum W}.\ F_{OPi}.\ F_{SRi}.\ F_{ARi}.F_{Di}\right) = 0.137$										

The obtained I_{RS} value of 0.12, when analyzed in the context of seismic assessment, falls within the specific range of 0.10-0.17, as outlined in Table 4.2 in Chapter 4. This range is associated with a "High priority" level of judgment for buildings located in a moderate seismic zone. This classification carries significant implications for the seismic safety of the structure in question. Being categorized under the "High priority" level indicates that the structure, while not in immediate or imminent danger of failure, does have discernible vulnerabilities that could be critical during a seismic event. These vulnerabilities might include structural weaknesses, inadequate connections, or materials that may not perform optimally under seismic stress. The "High Priority" designation is intended to be an unequivocal signal that the building requires extensive attention, particularly in the form of serious analysis and potential strengthening. In practical terms, this categorization means that the building can be subjected to a thorough seismic analysis to ascertain specific locations where its integrity can be compromised. So, based on what happened, we got to put some fixes in place. This might mean welding up some essential parts, reinforcing the building to handle earthquakes better, or even updating the design to meet today's safety rules. The goal is to make the building stronger, enabling it to withstand earthquake forces. By fixing the weak spots, we lower the chances of damage or collapse if an earthquake hits, which keeps people safe. Doing this ahead of time not only keeps people alive but also ensures the building remains intact, saving money on repairs later. Basically, the I_{RS} value of 0.12 puts this building into a high-priority group for earthquake zones, which means we really need to pay attention and maybe beef things up. This rating highlights the importance of implementing effective measures to strengthen the building and ensure everyone's safety during an earthquake.

5.3 Study Report on Application of RSAM on Existing URM Buildings

We used RSAM on ten old brick buildings, and the results are documented. We were cautious about checking how they'd handle earthquakes. First, we decided which buildings to check. Then, we used RSAM in two steps. We filled out a form with all the details and then assessed the strength of the walls. This helped us see if the buildings could survive an earthquake. Table 5.9 is important because it shows what each building is like – what it's made of and how big it is. It includes details like the height of the buildings, the thickness of the walls, and the number of walls compared to the floor space. It also shows how many windows and doors there are, and that all the buildings are made of brick. All the buildings are the same height (12 meters) and the walls are the same thickness (250 mm), which means they were built similarly. However, the number of walls and windows varies in each building, which in turn affects how they might behave during an earthquake. For example, building 04 has a lot of walls (86.8% in one direction), so it's probably stronger. Building 08 has fewer components, so it might not perform as well in an earthquake. Table 5.10 shifts its focus to the physical condition of the buildings, which is pivotal in establishing how the geometric and material properties influence the structural aging and deterioration. The table classifies the buildings based on their age, with all the buildings aged over 30 years, and then describes their degree of deterioration, vertical irregularity, and horizontal irregularity. The condition of these buildings ranges from 'minor' to 'severe' deterioration, with some (i.e., Buildings 01, 04, 07, and 10) exhibiting severe decline. Vertical and horizontal irregularities are also found, with most of the buildings having regular vertical patterns but varying degrees of horizontal irregularity. This is particularly significant as irregularity in form can lead to uneven distribution of stress during the seismic activity, thereby strengthening the effects of shaking and leading to structural failure. Finally, Table 5.11 provides the RS index (I_{RS}) of each building, the culmination of the application of RSAM. The I_{RS} is calculated for the x and y axes and provides an overall seismic risk rating. The results reveal that I_{RS} values vary across the buildings, with some, like Building 10, having a particularly low I_{RS} of 0.10 in the x-direction, indicating a high risk in the moderate seismic zone. Other buildings, such as Buildings 05 and 06, have higher I_{RS} values (e.g., 0.21). Still, these too are rated as high risk due to the overall seismic vulnerability indicated by their structural and material conditions. The table's final column categorizes the risk, with most of the buildings being rated as 'high' risk, signifying significant vulnerability to seismic events. The moderate ratings for Buildings 01, 07, and 08 suggest that these structures might fare slightly better in a seismic event, but they still present notable risks. The writing surrounding these tables is deliberate and methodical, guiding the reader through each step of the RSAM application while underscoring the significance of each piece of data. The description emphasizes the logical flow from the survey and geometric data to the physical condition assessment, culminating in the calculation of the RS index. The narrative effectively ties the tables together, demonstrating how the RSAM's findings align with the physical conditions and material properties detailed earlier, providing a comprehensive view of each building's seismic vulnerability. The discussion not only interprets the numerical data but also contextualizes it within the broader framework of structural safety, making it clear that these findings are crucial for informed decision-making regarding seismic risk mitigation.

Table 5.9 Geometric and material properties of the ten existing URM buildings.

Building No.	Height (m)	Wall Thickness (mm)		Length (m)		Wall Density (%) (x-dir.)/Floor Area	Wall Density (%) (y-dir.)/Floor Area	% Opening (X)	% Opening (Y)	Material
		Int.	Ext.	X	Y					
01	12	250	375	44.4	9.0	10	8.5	19.5	2.3	Brick
02	12	250	375	54.6	8.9	9.96	7.5	16.8	4.7	Brick
03	12	250	375	52.3	7.3	13.97	7.56	20.4	5.3	Brick
04	12	250	375	86.8	15.1	14	7.5	20.4	5.3	Brick
05	12	250	375	44.5	10.9	11.8	8.5	21.4	3.8	Brick
06	12	250	375	44.5	10.9	11.8	8.5	21.4	3.8	Brick
07	12	250	375	44.5	10.9	11.8	8.5	21.4	3.8	Brick
08	12	250	375	29.7	9.0	11.8	9.4	21.4	3.6	Brick
09	12	250	375	86.8	15.1	8.5	5.9	12.2	7	Brick
10	12	250	375	35.2	11.2	9.2	7.2	22.2	11.2	Brick

Table 5.10 Physical condition of the ten existing URM buildings.

Building No.	Age (yr.)	Deterioration	Vertical Irregularity	Horizontal Irregularity
01	>30	Severe	Regular	Regular
02	>30	Minor	Regular	Irregular
03	>30	Minor	Regular	Irregular
04	>30	Severe	Regular	Irregular
05	>30	Minor	Regular	Regular
06	>30	Minor	Regular	Regular
07	>30	Severe	Regular	Regular
08	>30	Minor	Regular	Regular
09	>30	Minor	Irregular	Irregular
10	>30	Severe	Regular	Irregular

Table 5.11 RS index of each URM building considered in the study.

Building No.	I_{RS} (x)	I_{RS} (y)	I_{RS}	Rating (Moderate Seismic Zone)
1	0.19	0.27	0.19	Moderate
2	0.15	0.16	0.15	High
3	0.16	0.11	0.11	High
4	0.16	0.11	0.11	High
5	0.21	0.3	0.21	High
6	0.21	0.3	0.21	High
7	0.19	0.24	0.19	Moderate
8	0.19	0.31	0.19	Moderate
9	0.15	0.15	0.15	High
10	0.10	0.19	0.10	High

From this data set, building 10 has the lowest I_{RS} (0.10), indicating it is in the best physical condition among the ten buildings. Conversely, Buildings 5 and 6 have the highest I_{RS} (0.21), suggesting they may have more significant issues or deficiencies. Buildings 2 and 9 share the same I_{RS} (0.15), placing them in a relatively better condition compared to the others, except Building 10. Buildings 3 and 4 have identical I_{RS} (0.16), indicating a similar condition, which is slightly worse than Buildings 2 and 9 but better than those with higher IRSs. Finally, Buildings 1, 7, and 8, all with an I_{RS} of 0.19, fall into the mid-range category of the condition spectrum. This distribution of I_{RS} values helps in prioritizing inspections, maintenance, and potential interventions, ensuring that buildings in poorer condition receive the necessary attention to enhance their safety and performance.

5.4 Verification of RSAM Application

There are three types of numerical methods used to validate the established visual rating method, including finite element modelling. One of them is the weighted shear strength factor (WSSF) method. This is basically the weighted shear stress factor of a URM building as obtained from the ratio of earthquake base shear stress demand over the shear strength of each masonry wall. WSSF defines the shear stress τ_i, calculated for each wall and divided by its associated τ_d to determine the shear resistance factor. The initial equation is shown in Equation 5.1.

$$\text{Shear strength factor, SSF} = \tau_i / \tau_d \tag{5.1}$$

When a weighted shear resistance factor is calculated for the entire building or element, the total area is also calculated, as shown in Equation 5.2.

$$\text{WSSF} = \Sigma(\text{SSF}_i \times A_i) / \Sigma(A_i) \tag{5.2}$$

A_i is the X-area of URM for each wall. After that, we use linear static analysis (LSA) to check how unreinforced masonry (URM) structures act. This means we create a simulation model to predict and analyze how the URM buildings bend when forces act on them. The FEM model thinks about how all the parts of the building work together, so we can get a solid idea of how these buildings act. To ensure the model is effective, we tune and test it with real data, focusing on the details of the masonry and potential breakdowns. This means closely modeling the materials, the building's structure, and how pressure is applied; all these factors affect the accuracy of the computer's prediction. The analysis results are shown by comparing the differences in shape among a group of ten different buildings. Both the results of the FEM analysis, along with the corresponding RSAM data, are fully depicted in Figures 5.3 and 5.4, respectively. These findings provide a graphical image of the structural deformations and validate the analytical solution through correlation of the theoretical and measured responses, hence bringing to light the reliability of the LSA method in the establishment of the stability and integrity of URM buildings. Walls' shell elements are employed in modelling, in which the shear-type auto hinge is used to simulate nonlinear response. A car wall mesh is chosen to ensure good discretization and accuracy in analysis. The modelling approach taken in this work renders the study of the structural behaviour more credible. Such assumptions facilitate the attainment of realistic deformation patterns under load. The complete material property table is provided in 5.12.

Table 5.12 The FE model is associated with material properties for both compression and tension.

Strain (-) Compressive (+) Tensile	Stress (MPa)
-0.006	-10.87
-0.005	-11.03
-0.000008	-13.79
-0.000007	-13.77
-0.000006	-13.44
-0.000005	-12.00
-0.000003	-8.14
0	0.00
0.001402	2.31
0.015417	0.00

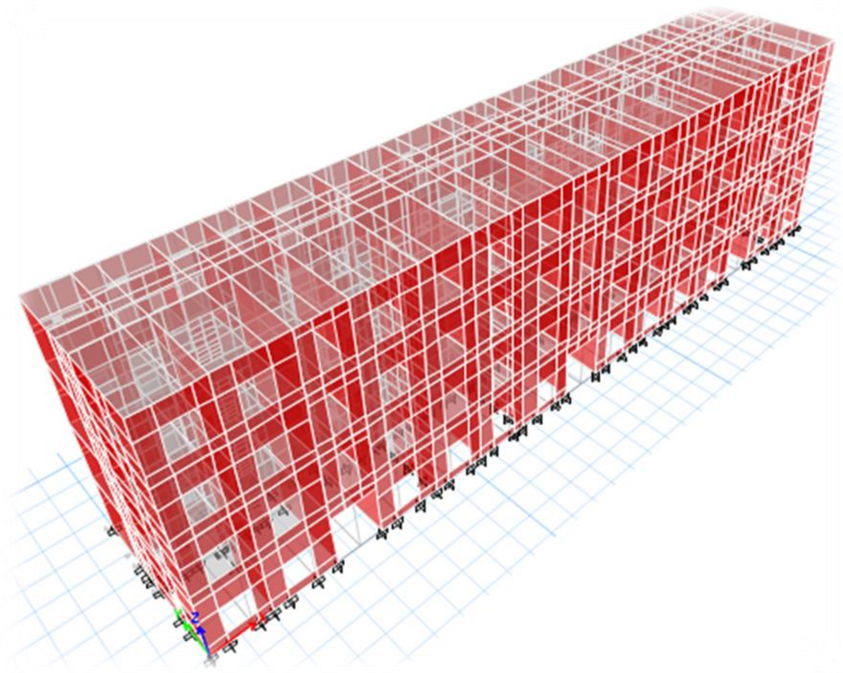


Fig. 5.3 Finite element (FE) model of URM full-scale building (Identical).

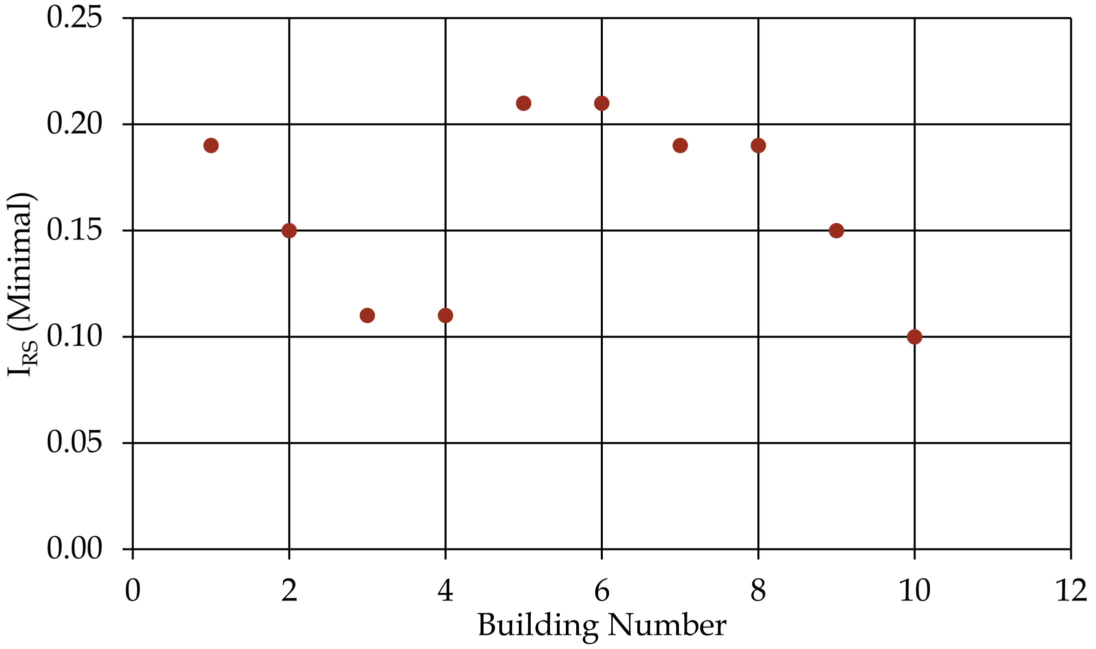


Fig. 5.4 I_{RS} results for the surveyed ten buildings.

In the final phase of the structural analysis, a complete pushover analysis (POA) is carried out. We used finite element modeling (FEM) after doing nonlinear static analysis, carefully putting plastic hinge features into the building parts. The iterated values are taken from the study carried out by Islam (2016, 2024). Adding these hinges is key to accurately mimicking where the structure might fail. This gives us a clearer idea of how the building will perform under extreme conditions. This modeling helps us understand how the whole building performs, particularly in terms of plastic drift, bending, and energy absorption. The POA method provides valuable insights into how the building behaves when pushed harder and harder from the sides, up to the point of severe damage or collapse. By observing where and how plastic hinges appear in critical areas, the study closely examines how the structure transitions from bending back into shape to maintaining its bent state. This helps determine how well the structure can withstand earthquake forces and how much energy it can absorb, a key indicator of its overall strength. As FEMA 273 suggests, we maintained thorough notes and closely examined our findings. Figure 5.5 shows what happened when we used the weighted shear strength factor (WSSF) method, with guesses of how the building would bend and where the structure might break. We then compared those results to the energy use curve from the pushover study in Figure 5.6. The energy use graph helps illustrate how much energy the building can absorb before reaching its limit, thereby demonstrating its seismic performance. As a further check on the validity of the analysis, I_{RS} scores are calculated. They are provided for a sample ten-building population, each building having four storeys. The I_{RS} scores were systematically compared among these buildings. To examine more in detail, the I_{RS} scores are compared for two extreme cases, which are well documented in Tables 5.13 and 5.14. These tables provide a comparison of the I_{RS} scores, which show the range of variability of the seismic behavior of the most and least robust structures in the sample, giving valuable information on the range of variability of the structural responses in the sample.

Table 5.13 Analyzed data for building B05.

Dir	B05	LSA	WSSF	POA
	I_{RSAM}	(kN, Drift %)	Index	Lateral Strength
x	0.2	5000, 0.02	1.15	high

Table 5.14 Analyzed data for building B10.

Dir	B10	LSA	WSSF	POA
	I_{RSAM}	(kN, Drift %)	Index	Lateral Strength
x	0.1	4300, 0.04	1.41	low

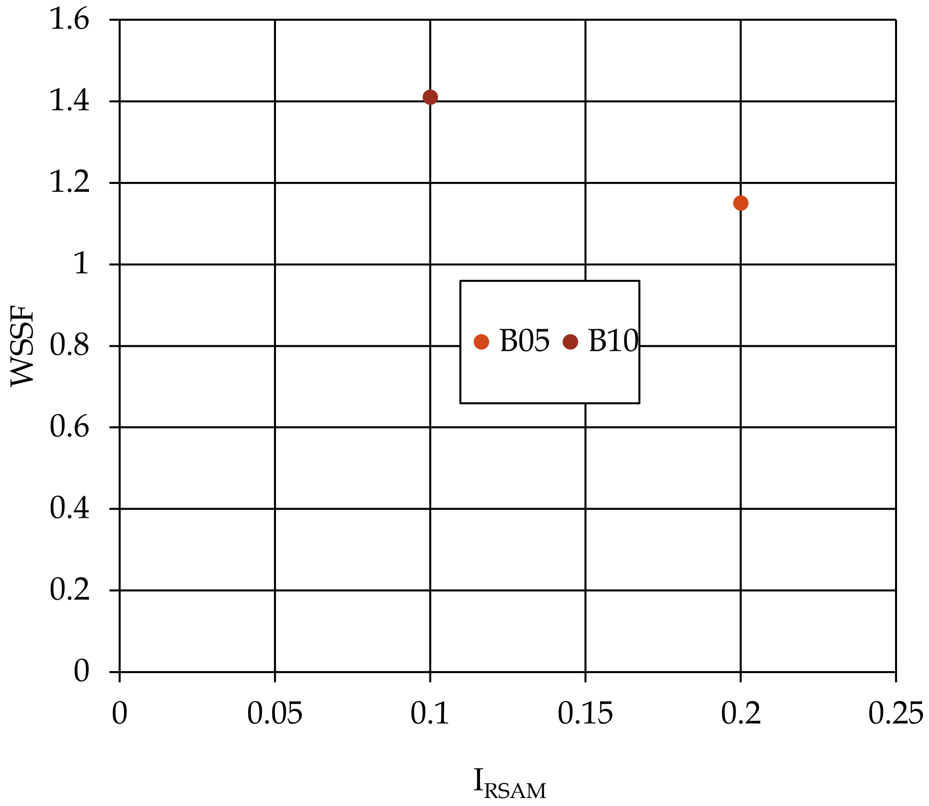


Fig. 5. 5 WSSF and I_{RSAM} result comparison for two extreme cases.

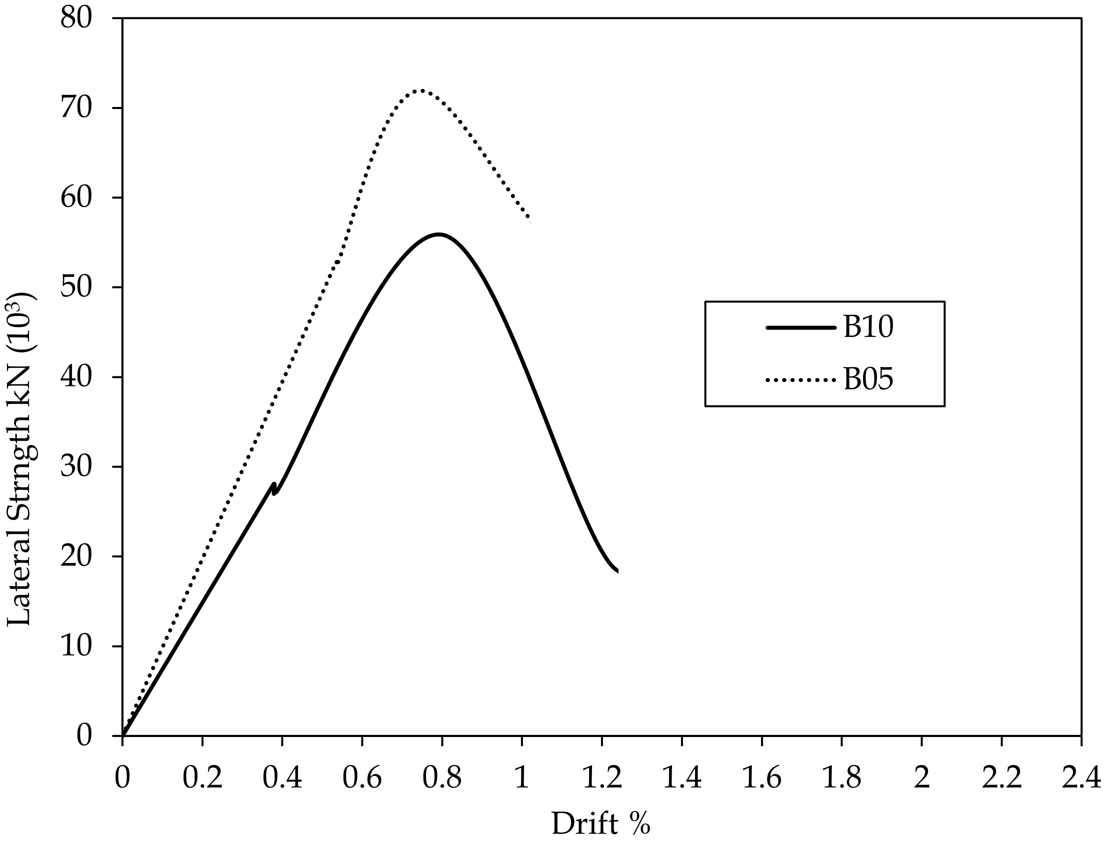


Fig. 5. 6 Push over analysis result comparison for two extreme cases.

The results of Buildings B05 and B10, from the above Figures and Tables, demonstrate a significant variation in their seismic structural response. For Building B05, the linear static analysis (LSA) indicates an effective structural response with a relatively small deformation (drift) of 0.02% in response to a base shear of 5000 kN. This means that B05 will be capable of withstanding strong lateral forces with minimal deformation, as a reflection of its strength in the linear elastic range. The equivalent static analysis (ESA) of B05, which had a weighted shear strength factor (WSSF) value of 1.15, shows an even seismic force distribution, further stabilizing the overall stability of the building. On the other hand, Building B10 has a lower I_{RS} value of 0.1 for the LSA, with a base shear of 4300 kN and a higher drift percentage of 0.04%. This shows poorer structural response, with B10 experiencing more deformations under less severe seismic forces compared to B05. The ESA value for B10, with a corresponding WSSF value of 1.41, is indicative of an inefficient force distribution of seismic forces, and thus higher stress concentrations and potential failure points. The POA results also indicate this shortcoming with a low lateral strength value, offering an indication of poor energy dissipation capacity, leading to a higher chance of structural failure under seismic loading. The relative comparison, as indicated by Figures 5.5 and 5.6, brings out these differences between the two buildings. Figure 4.4 compares WSSF and I_{RS} results and makes evident that Building B05, whose base shear capacity is higher and whose drift is negligible, possesses superior seismic performance. Building B10, whose base shear capacity is lower and whose drift is higher, demonstrates a less stiffened response to seismic forces. Fig. 5.6, which compares the pushover analysis results, shows that Building B05's energy dissipation curve is smoother in its transition to the inelastic range, implying it dissipates more energy before sustaining significant damage. Building B10's curve will change faster to the inelastic range and won't waste as much energy, which says it's not as tough. Overall, the study shows Building B05 handles earthquakes better than Building B10. Since Building B05 can withstand larger earthquake forces with minimal modifications and consumes less energy, it's a more resilient structure during earthquakes. Still, Building B10 is weaker and changes more under the same conditions, so it's more likely to fail. That underlines how important it is to conduct a complete nonlinear analysis to predict how well buildings will withstand earthquakes.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The Rapid Seismic Assessment Method (RSAM) is proving to be a valuable tool for quickly assessing the seismic performance of unreinforced masonry (URM) walls. It helps manage earthquake risk, especially in crowded cities where earthquakes can be potentially dangerous. RSAM aids inspectors and engineers to go through quickly and easily determine how likely a building is to be damaged in a future earthquake. It considers aspects such as the walls, columns, and foundation. Because of its quick and easy application, RSAM is useful when you need to check a large number of buildings within a short period of time. So, the government and experts can utilize limited resources to fix the buildings that are most likely to collapse first. This really matters when we don't have a lot of time, financial aid, or people to help, since it allows us to use what we have wisely and effectively, enabling more people to take steps before an earthquake occurs.

6.2 Conclusions

This research introduces a novel approach to assessing existing unreinforced masonry (URM) buildings. The study proposes a Rapid Seismic Assessment Method (RSAM) as a quick and cost-effective tool to assess the seismic vulnerability of existing URM buildings, referring to the priority setting of buildings requiring detailed seismic evaluation. The major findings can be stated as follows:

a) The developed RSAM represents a substantial advancement over the widely used Rapid Visual Screening (RVS) technique. Unlike traditional methods, RSAM eradicates the dependency on existing seismic damage databases, which makes it usable in data-scarce regions. It incorporates a comprehensive set of parameters that could potentially influence the seismic performance of URM buildings, considering a more holistic approach to vulnerability assessment.

b) The method introduces an index (I_{RS}), which quantifies critical building characteristics. These characteristics include wall-to-height ratios, overall building proportions, construction age, visible structural condition, and identifiable seismic risks such as pounding effects and large openings. The I_{RS} serves as a decision-making indicator to prioritize buildings that may require urgent, detailed structural evaluations and retrofitting measures.

c) Field application of RSAM in the considered context demonstrates that the I_{RS} correlates closely with analytical simulations of seismic vulnerability assessments of full-scale URM buildings. The seismic capacity-demand-based categorization chart opens a wide boundary of application in different regions of the world.

In summary, the study shows that RSAM is a user-friendly and effective prediction tool, which involves setting priorities. RSAM can help engineers, architects, city planners, and disaster management stakeholders to take active steps to minimize the risks, plan for emergencies, and make cities earthquake resilient.

6.3 Recommendations

The following recommendations are made to enhance the effectiveness and utility of RSAM.

a) The incorporation of new-age technologies, such as digital tools, remote sensing, and machine learning algorithms, simplifies the process of visual observation and evaluation of different items. These technological developments would enable better evaluations, allowing RSAM to adapt to changing seismic assessment needs.
b) Formulation of detailed guidelines and standard operating procedures for the use of RSAM to increase its reliability and utility in seismic assessment. Guidelines should be developed by industry experts, regulators, and universities working together to make them robust and widely accepted. Clear standards will increase uniformity in the use of RSAM in applications and allow for broader use.
c) Institutionalized training of engineers, inspectors, and other interested parties to support the proper use of RSAM. Practice should be included in training, and users should be well-versed in the method, including its strengths and limitations. Training will enhance the quality of assessments and ensure that RSAM is used only in appropriate settings.
d) Piloting projects and case studies to provide information on the actual use of RSAM in different settings. These projects can be used to draw attention to potential problems and to strengthen the method and best practices. By analyzing real use, researchers and practitioners can improve RSAM and avoid issues that have been encountered.
e) Collaboration and information exchange between researchers, practitioners, and policymakers is essential to the continued improvement of RSAM. The creation of platforms for experience and best practice sharing will ensure the method's strength and further enable its use. Collaborative multi-stakeholder involvement will increase innovation and ensure that RSAM is continually a strong, effective, and useful seismic assessment tool.
f) Encouragement of the use of RSAM in local and national seismic safety laws to make it widely used. The inclusion of RSAM in policy to guarantee more disaster-resilient building processes and better overall community protection. The policy integration will make RSAM a normative element in seismic hazard reduction planning processes, which will increase safety processes and earthquake preparedness.

6.4 Future Studies Proposals

Future work should focus on some of the following key research streams to take RSAM and its application to the next level:

a) Future work should focus on the integration of more advanced models, such as full-scale micro finite element models, full-scale shake table tests, and machine learning models, to increase the accuracy of the RSAM prediction. These models will provide more sensitivity to the seismic vulnerability and make the technique more adaptive in different regional contexts.
b) Maintenance and development of large building databases will help to provide more accurate and efficient seismic vulnerability evaluations. An organized database will provide information on building characteristics and previous

performance that will be extremely helpful in updating RSAM and more accurately predicting.

c) Future research may involve testing the practical application of RSAM in many real contexts through pilot studies and case studies. This experimentation will help identify weaknesses, refine the method, and upsize RSAM to various urban and rural contexts and building types.

d) Future studies may focus on quantifying the effects of the integration of RSAM in seismic safety policies and legislation. Quantifying the impact of integrating policy on the implementation and efficiency of RSAM can help enforce resilient constructions and safer communities.

By filling these gaps, future work will contribute to the ongoing refinement of RSAM, making the method a more practical tool for seismic vulnerability analysis. This, in turn, will help to achieve better earthquake disaster readiness and resilience towards sustainable and resilient infrastructure.

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