Improved Rapid Assessment of Earthquake Hazard Safety of Existing Buildings Using a Hierarchical Type-2 Fuzzy Logic Model

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Date: 26 Mai 2020

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Dedication

This thesis is dedicated to my precious parents, my lovely sister and brother, and to the soul of my grandmother and my professor at the Universiti Teknologi Malaysia (UTM) Prof. Abdul Kadir Marsono for their continuous support and encouragement.

Abstract

Although it is impractical to avert subsequent natural disasters, advances in simulation science and seismological studies make it possible to lessen the catastrophic damage. There currently exists in many urban areas a large number of structures, which are prone to damage by earthquakes. These were constructed without the guidance of a national seismic code, either before it existed or before it was enforced. For instance, in Istanbul, Turkey, as a high seismic area, around 90% of buildings are substandard, which can be generalized into other earthquake-prone regions in Turkey. The reliability of this building stock resulting from earthquake-induced collapse is currently uncertain. Nonetheless, it is also not feasible to perform a detailed seismic vulnerability analysis on each building as a solution to the scenario, as it will be too complicated and expensive. This indicates the necessity of a reliable, rapid, and computationally easy method for seismic vulnerability assessment, commonly known as Rapid Visual Screening (RVS). In RVS methodology, an observational survey of buildings is performed, and according to the data collected during the visual inspection, a structural score is calculated without performing any structural calculations to determine the expected damage of a building and whether the building needs detailed assessment. Although this method might save time and resources due to the subjective/qualitative judgments of experts who performed the inspection, the evaluation process is dominated by vagueness and uncertainties, where the vagueness can be handled adequately through the fuzzy set theory but do not cover all sort of uncertainties due to its crisp membership functions. In this study, a novel method of rapid visual hazard safety assessment of buildings against earthquake is introduced in which an interval type-2 fuzzy logic system (IT2FLS) is used to cover uncertainties. In addition, the proposed method provides the possibility to evaluate the earthquake risk of the building by considering factors related to the building importance and exposure. A smartphone app prototype of the method has been introduced. For validation of the proposed method, two case studies have been selected, and the result of the analysis presents the robust efficiency of the proposed method.

Keywords: Rapid Visual Assessment, Fuzzy logic, Seismic Vulnerability, Uncertainty, Reinforced concrete building

Kurzfassung

Problemstellung und Zielsetzung

Erdbeben sind Naturkatastrophen, welche Bauwerke schädigen, Gefahr für Leib und Leben darstellen und finanzielle und soziale Verluste verursachen. Aufgrund der stochastischen Natur der Erdbeben ist die Schadens- und Standsicherheitsbewertung von Tragwerken während des Erdbebens, insbesondere im städtischen Maßstab, eine anspruchsvolle Aufgabe. Die Mehrheit der Bestandsgebäude in erdbebengefährdeten Regionen entspricht nicht den Anforderungen moderner Vorschriften und benötigt daher eine genauere Bewertung, um sie auf ein angemessenes Niveau nachzurüsten und so Schäden durch seismische Aktivitäten zu minimieren.

Die Mehrheit der Methoden zur Bewertung der seismischen Anfälligkeit von Gebäuden beinhaltet eine detaillierte Strukturanalyse, welche durch die benötigte große Anzahl an detaillierten, technischen Informationen sehr zeit- und kostenintensiv ist. Um die Gebäude für eine umfassende Bewertung zu filtern und zu priorisieren, werden alternative Methoden des Rapid Visual Screening (RVS) entwickelt. Eines der Ziele dieser Arbeit ist die Verbesserung der aktuellen Methoden zur schnellen Schadensbewertung.

Eine Bewertung auf Grundlage einer Begehung, welche auch bei einem großen Gebäudestand ressourcenschonend ist, ist anfällig für die Subjektivität der Inspizierenden Personen. Darüber hinaus wird die Entscheidung durch die verschiedenen Versagensarten beeinflusst, was eine risikobasierte Bewertung erfordert. Daher besteht die Notwendigkeit, eine risikobasierte RVS-Methode und ein Werkzeug zu entwickeln, um mangelhafte Gebäude zu filtern, Prioritäten für die weitere Untersuchung zu setzen und die Unsicherheiten zu berücksichtigen. All diese Problemstellungen werden in dieser Arbeit mit Hilfe eines Unschärfe-Logik-Modells vom Typ 2 (type-2 fuzzy logic model) behandelt.

Das Hauptziel dieser Arbeit ist es, die schnelle visuelle Bewertung der Schädigung zu verbessern und das Erdbebenrisiko von Stahlbetontragwerken zu beurteilen. Daher wird ein zweistufiges, auf Unschärfe-Regeln basierendes Modell zur Priorisierung von Gebäuden nach ihrer Schwachstelle bei Erdbeben vorgeschlagen. In diesem Modell wird jede Unsicherheit aufgrund des subjektiven Urteils der Bewertung nach einer Begehung mit Hilfe der Typ-2-Unschärfemengentheorie (type-2 fuzzy set theory) behandelt.

Stand der Wissenschaft

Seismischen Prüfungsmethoden werden in beobachtende und vorhersagende Vulnerabilitätsverfahren und deren Kombination eingeteilt. Beobachtende Vulnerabilitätsverfahren verwenden Statistiken und Expertenmeinungen über Schäden vergangener Erdbeben, um das voraussichtliche Verhalten der Bauwerke bei zukünftigen Ereignissen zu bestimmen. Das Hauptproblem dieses Ansatzes ist der mögliche Mangel an vorhandenen Daten, die Subjektivität bei deren Interpretation und die fehlende analytische Grundlage. Vorhersagende Vulnerabilitätsverfahren nutzen daher analytische Ansätze zur Bestimmung des wahrscheinlichen Tragwerkverhaltens für eine Bemessungs-Erdbebenbelastung. Dieser Ansatz wird jedoch durch den Zeit- und Rechenaufwand einer detaillierten Systemanalyse beschränkt. Daher muss ein ausgewogenes Verhältnis zwischen geringem Aufwand je evaluiertem Gebäude und hoher Genauigkeit gefunden werden. Weiterhin muss das neue Modell eine Verbesserung der Genauigkeit und Korrelation zwischen dem Ergebnis der Schadensbewertung und den schnellen Bewertungsmethoden beinhalten.

Neben nationalen und technischen Methoden werden in der Literatur drei weitere Ansätze vorgeschlagen. Auf statistischen Ansätzen basierende Methoden reduzieren die nichtlineare Beziehung zwischen Gebäudeparametern, Seismizitätsparametern und Schädigungsfähigkeit auf eine lineare Beziehung zwischen Ein- und Ausgabe. Methoden, die auf maschinellem Lernen und ANNs-Ansätzen basieren, benötigen eine große Anzahl an Trainingsdaten über Gebäudeparameter und der Schadensart nach den Erdbeben. Existieren diese nicht, sind solche Ansätze wenig praktikabel. Darüber hinaus sind diese Ansätze lokal und auf ein bestimmtes Gebiet beschränkt. Die letzte Art der Methoden berücksichtigen in den Unschärfe-Systemen die Meinung von Experten, wobei die Beschreibung der Unschärfe der Gebäudeparameter linguistisch vorgenommen wird.

Unschärfe-Systeme tragen zu bedeutenden Erfolgen bei der Anfälligkeitsbewertung bei, da sie auf Grundlage unpräziser oder mehrdeutiger Daten endgültige Entscheidungen treffen konnten. Das Hauptproblem aller bisherigen Studien, die auf dem herkömmlichen Fuzzy-Logic-System (Typ 1) basieren, besteht darin, dass sie nur die Vagheit der Zugehörigkeitsfunktionen berücksichtigen, aufgrund der klaren Zugehörigkeitsfunktionen jedoch nicht alle Arten von Unsicherheiten einbeziehen. Diese Arbeit schlägt daher eine Methode vor, die auf dem hierarchischen Typ-2-Fuzzy-System basiert, um die Schwäche der bestehenden unschärfebasierten RVS-Methoden zu überwinden.

Eingesetzte Methoden

Das Hauptziel dieser Arbeit ist es, die visuelle Schnellbewertung der Anfälligkeit zu verbessern und das Erdbebenrisiko von Gebäuden mit einem Stahlbetontragsystem zu bewerten. Dazu wird ein hierarchisches zweistufiges Unschärfe-Regel-basiertes Modell zur Priorisierung von Gebäuden entsprechend ihrer Anfälligkeit bei Erdbeben vorgeschlagen. In jeder Stufe werden die Unsicherheiten aufgrund des subjektiven Urteils einer Bewertung durch eine Begehung oder der Bewertungsverfahren mit Hilfe des Intervall-Typ-2-Fuzzy-Logic-Systems (IT2FLS) behandelt.

In der ersten Phase wurde ein Modell zur Bewertung der Erdbebengefährdung von Gebäuden entwickelt. Die berücksichtigten Parameter, welche sich leicht durch eine Begehung und technische Zeichnungen ermitteln lassen, stimmen mit FEMA P-154 (2015) überein: i) Bodentyp, ii) seismische Zone, iii) Anzahl der Stockwerke, iv) Gebäudetyp, v) vertikale Unregelmäßigkeit, vi) Planunregelmäßigkeit, vii) Baujahr und viii) Bauqualität.

In der zweiten Phase wurden die Bedeutung und Exposition der Gebäude sowie weitere Parameter wie Gebäudenutzung, Belegung und Zeitpunkt des Ereignisses unter Verwendung eines hierarchischen Unschärfe-Modells zur Bewertung des Erdbebenrisikoindex des Gebäudes in das entwickelte Model der ersten Phase integriert. Dieser Teil kann zur Risikobewertung vor als auch zur Ermittlung des anfänglichen und unmittelbaren Ausmaßes des Risikos nach dem Erdbeben (z.B. zur Gebäudepriorisierung für Rettungs- und Notfalldienste) eingesetzt werden.

Ferner beinhaltet die Arbeit eine Bewertung und einen Vergleich der Wirksamkeit der vorgeschlagenen Methode mit tatsächlich geschädigten Gebäuden aus zwei Fallstudien und den Vergleich mit anderen gebräuchlichen Methoden, die mit den gleichen Daten bearbeitet wurden.

Wesentliche Ergebnisse

Das neue, einfache zweistufige Modell ermöglicht eine schnelle Bewertung der seismischen Anfälligkeit und des Risikoindexniveaus von Gebäuden, wobei alle Ungenauigkeiten, die mit der subjektiven Bewertung von Stahlbetongebäuden verbunden sind, durch IT2FLS abgedeckt werden.

Die vorgeschlagene Methode wurde in einer einfachen und überschaubaren hierarchischen Struktur angelegt. Dies hat eine Minimierung der Regeln des Unschärfe-Logik-Systems, eine Erhöhung der Berechnungsgeschwindigkeit, eine Problemvereinfachung sowie die Reduzierung des Berechnungsaufwands zur Folge.

Die Anwendung dieser Methode ist nicht wie andere auf eine bestimmte Region begrenzt, sondern lässt sich leicht modifizieren und aktualisieren, sodass sie für jeden Standort verwendet werden kann. Zusätzlich ist sie einfach zu bedienen und benutzerfreundlich gestaltet, wodurch jede Anwenderin bzw. jeder Anwender mit etwas Hintergrundwissen und kurzer Schulung damit arbeiten kann. Diese Methode ist flexibel genug, um neue Schadensmechanismen einzubeziehen.

Die Robustheit der vorgeschlagenen Methode wurde nachgewiesen, nachdem 512 verschiedene Gebäude aus verschiedenen Städten, welche von Erdbeben betroffen waren, in Fallstudien untersucht worden waren. Es wurde gezeigt, dass die bewertete Anfälligkeitsklasse sehr nahe an der tatsächlichen Schadenshöhe lag, die bei den Gebäuden beobachtet wurde. Dies ergibt im Vergleich zu früheren Methoden eine zuverlässigere Verteilung zwischen den verschiedenen Schadenshöhen.

Die vorgeschlagene Methode ist entsprechend der getätigten Forschung genauer als andere Methoden. Im Vergleich zu gängigen nationalen Methoden wurde die Genauigkeit um etwa 30 bis 40% signifikant verbessert. Auch im Vergleich zu Methoden des maschinellen Lernens konnte eine Verbesserung von etwa 12 bis 16% erzielt werden. Neben den finanziellen Vorteilen und einer besseren Planung des Naturkatastrophenmanagements macht diese Leistung auch die Nachrüstung von Gebäuden intelligenter und rettet das Leben der Bewohnerinnen und Bewohner.

Die risikobasierte Priorisierung umfasst Aspekte der technischen Entscheidungsfindung, wie z.B. die Schadensabschätzung und den gesellschaftlichen Wert (bspw. die Toleranz gegenüber den Folgen des Versagens).

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List of Abbreviations

ANNs	Artificial Neural Networks
BCPI	Basic Capacity Index
BO	Building Occupancy
BP	Back Propagation
BS	Basic Score
BU	Building Use
C	Collapse
CEN	European Committee for Standardization
CI	Column Index
CNN	Convolution Neural Network
CPI	Capacity Index
CQ	Construction Quality
CT	Classification Tree
DR	Decrease In Resistance
DRR	Disaster Risk Reduction
DVA	Detailed Vulnerability Assessment
EHSAPP	Earthquake Hazard Safety Assessment via Smartphone App
EKM	Enhanced Karnik-Mendel
EMPI	Earthquake Master Plan for Istanbul
EMS-98	European Macroseismic Scale-98
EN	European Standard
EPS	Expected Performance Score
FEMA	Federal Emergency Management Agency
FIS	Fuzzy Inference System
FLDA	Fisher's Linear Discriminant Analysis
FL-RVSP	Fuzzy Logic-based Rapid Visual Procedure
FOU	Footprint of Uncertainty
GIS	Geographic Information System
GNDT	National Earthquake Defense Group of Italy
GPS	Global Positioning System
GSDMA	Gujarat State Disaster Mitigation Authority
I^{BV}	Index of Building Vulnerability
ID	Increase in Demand
I^{EHS}	Index of Earthquake Hazard Safety
I^{EP}	Initial Evaluation Procedure

I^{ER}	Index of Earthquake Risk
IITK	Indian Institue of Technology Kanpur
IO	Immediate Occupancy
IOPC	Immediate Occupancy Performance Classification
IS (1893:2002)	Indian Standard (1893:2002)
I^{SSC}	Index of Seismic Site Condition
IT2FLS	Interval Type-2 Fuzzy Logic System
JPDPA	Japanese Building Disaster Prevention Asociation
KM	Karnik-Mendel
KNN	K-Nearest-Neighbor
L	Light
LMF	Lower Membership Function
LS	Life Safety
LSPC	Life Safety Performance Classification
M	Moderate
MCDM	Multi-Criteria Decision Making
MCE	Maximum Considered Earthquake
METU	Middle East Technical University
MF	Membership Function
MIDR	Maximum Inter-Story Drift Ratio
MLP	Multi-Layer Perceptron
MLR	Multiple Linear Regression Analysis
MNLSI	Minimum Normalized Lateral Strenght Index
MNLSTFI	Minimum Normalized Lateral Stiffness Index
N	Number of Story
NBS	New Building Standard
NEHRP	Natural Hazard Reduction Program
NN	Neural Network
NRCC	National Research Council Canada
NRS	Normalized Redundancy Score
NZSEE	New Zealand Society for Earthquake Engineering
O	None (as a damage level)
OASP	Earthquake Planing and Protection Organization of Greece
OLS	Ordinary Least Square
OPS	Observed Performance Score
OR	Overhang Ratio

PB	Post-Benchmark
PC	Pre-Code
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PI	Plan Irregularity
PI	Priority Index
PLSDA	Partial Least Squares Discriminant Analysis
PS	Performance Score
RC	Reinforced Concrete
RF	Random Forest
RSP	Rapid Screening Procedure
RVS	Rapid Visual Screening
S	Severe
SD	Structural Deficiency
SERU	Structural Engineering Research Unit
SPI	Seismic Priority Index
SS	Structural System
SSI	Soft Story Index
ST	Soil Type
SVA	Simplified Vulnerability Assessment
SVM	Support Vector Machine
SZ	Seismic Zone
T	Time of Event
T1FLS	Type-1 Fuzzy Logic System
T2FLS	Type-2 Fuzzy Logic System
UMF	Upper Membership Function
USGS	United State Geological Survey
VI	Vertical Irregularity
WI	Wall Index
YC	Year of Construction

List of Symbols

$\tilde{}$	Indicates fuzzy set is a Type-2 fuzzy set
$\int$	Indicates the collection of all points (Not integration)
$\cup$	Indicates the maximum operation
$\cap$	Indicates the minimum or product t-norm operation
M_S	Surface wave magnitude
M_W	Moment magnitude
V_{S30}	Shear wave velocity for the top 30 m of soil

Chapter 1

Introduction

1.1 Background of the Study

As the world's population, urbanization developments, and megacities grow, the economic impacts of natural disasters continue to rise [56]. The recent medium- and strong-intensity earthquakes have caused high economic losses and have highlighted the key role of the high vulnerability of existing buildings (private or public), structures, and infrastructure. Often, they have been designed without anti-seismic or with old seismic criteria, and have been responsible for a significant amount of seismic losses. Consequently, as a result of the high number of buildings, structures, and infrastructure requiring retrofitting interventions, mitigation strategies based on accurate approaches must be defined [10]. In fact, despite recent research advances, significant improvements are still needed. Tools that can be applied directly must be developed and promoted so that effective decisions can be made to reduce the destructive effects of earthquakes.

To mitigate the seismic risk and reduce direct and indirect losses, public administrations, insurance companies, banks, owners, and professionals, despite operating at different territorial scales and with different objectives and tools, should perform a synergic work based on rational criteria and tools. The effectiveness and reliability of the assessment and the resulting seismic risk mitigation strategies should be based on tools and models that can simulate seismic effects, in terms of direct and indirect losses. To evaluate and mitigate the seismic risk for existing buildings, structures, and infrastructure, as well as different territorial scales (down to the analysis of individual buildings), different assessment methods and factors can be considered.

Failure of structures is the main cause of higher deaths and injuries during an earthquake [71], while also causing increased economic loss [37]. Studies showed that the behavior of different structure types during an earthquake and their vulnerability depends mainly on the primary vertical load-bearing elements [18]. In other words, different construction methodologies have different levels of vulnerability. For instance, a masonry building with walls as load-bearing elements without any frame structure might be more vulnerable compared to that of a reinforced concrete (RC) structure with columns as load-bearing elements with a moment-resisting frame [160]. The damage caused to a building during an earthquake can be estimated by assessing seismic vulnerability [130]. "Seismic vulnerability" is defined as "the susceptibility of a population of buildings to undergo damage due to seismic ground motion" [11].

An earthquake (seismic) risk can be assessed by taking into account the earthquake hazard, the vulnerability of building, and the importance/exposure factor (consequence of failure) [192], as has been noted in Eq. 1.1, where the earthquake hazard describes the intensity and probability of an earthquake event, the vulnerability and importance that estimate the performance of a variety of building types to different levels of seismic loading considering different factors, respectively, the risk is then the proportion of buildings that are likely to fail. Earthquake risks assessments are used by property owners, tenants, investors, city/country authorities, lenders and others to understand and manage earthquake-related risks.

$$Risk = Hazard \times Vulnerability \times Exposure \tag{1.1}$$

If earthquake risk assessment is viewed as Heinrich's domino theory of cause and effects [153], damage results from a chain of sequential events, metaphorically like a line of dominoes falling over. A perception of earthquake risk assessment labeled on five metaphorical dominoes in the sequences, as shown in Figure 1.1. Where the first piece is the seismic hazard, which plays an important role and is inherently unavoidable, followed by the building vulnerability, then construction characteristics, which lead to seismic risk and damage on building and cause loss and injury of residents, respectively. When one of the dominoes falls, it triggers the next one, and the next, but improving or removing a key factor (such as retrofitting buildings) prevent or minimize the impact of the chain reaction of dominoes. As it is not possible to modify the seismic hazard to reduce the risk, emphasis should be placed on the study of vulnerability and vulnerability reduction as a measure of damage/loss mitigation. However, increasing awareness of the people and preparing rescue plans could play a significant role in exposure and the number of affected people.

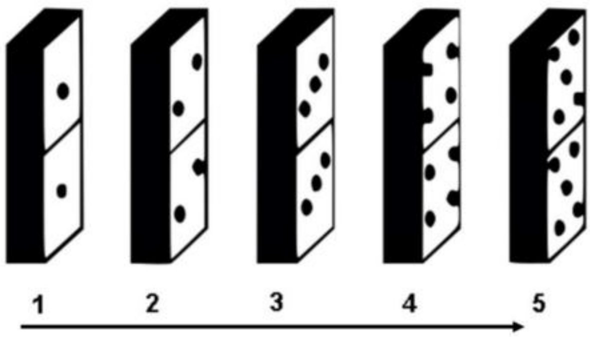


Figure 1.1: Domino's sequences of earthquake risk assessment

Earthquake risk and vulnerability assessment identify the susceptibility of target building stock to earthquake vibrations. Under those circumstances, property owners (or authorities) could perhaps prefer to implement strengthening techniques such as seismic retrofitting or as advised by the local ordinance and regulations. In such situations, the requirement to analyze the behavior of structure by virtue of seismic excitation is highly consequential to reduce possible damage due to future seismic events. Therefore, earthquake and structural engineers would be needed to recognize the inadequacies in existing structures and to strengthen it. There are some prime aspects that need to be taken into compliance during the design of retrofit system, such as the national seismic code, local building standards, engineering constraints, the economic background, and demands of authorities or property owners.

1.2 Research motivation

There are many methods available for seismic vulnerability assessment of buildings, which involve detailed structural analysis and design [44]. These detailed assessment methods consume more time when the assessment must be performed for a large number of buildings [174]. To filter and prioritize the buildings for comprehensive, time- and resource-saving assessment, alternative Rapid Visual Screening (RVS) methods have been developed [87].

Generally, most of the evaluation procedures follow a three-stage assessment process, which starts with a rapid visual assessment to categorize buildings into different damage categories based on seismic vulnerability, which will be discussed in depth in this thesis. Afterward, a detailed assessment using structural components, material properties, and site conditions are performed for the critical buildings. If necessary, the selected buildings from the detailed assessment are evaluated by third-stage assessment, which involves sophisticated in-depth structural analysis [157]. For instance, the study on estimating the floor deformability in existing RC buildings [165] or proposing improvement on the reliability and accuracy in vulnerability modeling [176].

The seismic risk assessment demands consideration of site seismic hazard, building vulnerability, and building importance and exposure factors, which require a multidisciplinary method. With a high inventory of buildings, however, a thorough investigation of individual buildings is not feasible due to limited human resources and available funds, which highlights the importance of using a simple walk-down survey. However, the walk-down survey is prone to the subjectivity of the evaluator, and vagueness uncertainty is introduced. Furthermore, the final decision is influenced by different consequences of failures, which commands risk-based assessment. Thus, there is a need for developing a risk-based RVS method and tool to screen out deficient buildings and prioritizing for further investigation. Moreover, the proposed method needs to consider the vagueness and cover uncertainty.

1.3 Aim and objective

The main aim of this thesis is to improve the rapid visual vulnerability assessment and evaluate earthquake risk of RC buildings by proposing a two-stage fuzzy rule-based model to prioritize buildings according to their vulnerability during earthquakes. Our objectives include:

- Studying existing rapid visual seismic vulnerability assessment methods and prepare an actual state-of-the-art review
- Covering the epistemic uncertainty and variability of the hazard safety assessment parameters
- Reducing the computational cost and power by finding a simplified structure for proposed fuzzy model
- Developing a novel and yet simple two-stage model, intuitive integration of different building performance modifiers obtained from a walk-down survey and engineering drawings.
  - Stage 1: Evaluating the earthquake hazard safety of buildings and prioritize them
  - Stage 2: Integrating the importance and exposure of the building into Stage 1 using a hierarchical heuristic model to assess the building's earthquake risk index.
  - Note: in each stage, any uncertainty due to the subjective judgment of the walk-down survey or evaluation procedures is handled using the interval type-2 fuzzy set theory
- Proposing a method that can be useful for pre- and post-earthquake management purposes
- Assessing and comparing the effectiveness of the proposed method with actual damage and other methods using case studies

- Developing a prototype of a smartphone app based on the proposed method to simplify and accelerate the collection and processing of data online

1.4 Scope and Delimitations of the Study

The scope of this study is as follows:

- Focus on short to medium-rise RC buildings
- Manifest the applicability of procedures by using case studies
- Identify the most common parameters for earthquake hazard safety assessment and building importance/exposure to achieve earthquake risk level
- Review available literature up to the date of the research period
- Present the procedures and prepare a thesis

1.5 Thesis structure

This thesis is presented as the following chapters:

- **Chapter 1 Introduction:** The current chapter presents a generalized idea about this research work. It elaborates on the aim and objectives to be achieved in due process.

- **Chapter 2 Literature Review:** This chapter provides an insight into the current state of previous and recent studies and their limitations while describing various RVS methods and seismic vulnerability assessment. From here, the research gap and problem statements are identified.

- **Chapter 3 Research Methodology:** The defined problem has been tackled in this chapter. It begins with the definition of soft computing technique and focuses on the type-1 fuzzy and interval type-2 fuzzy theory. The conceptual implementation and detailed description of the proposed methodology is illustrated here.

- **Chapter 4 Results and Discussion:** The validity, applicability, and efficiency of the proposed method is examined by performing two case studies. The assessments by the proposed method are compared to the real observed damage of the building, and other applied RVS methods to the same database. In addition, some data analysis and description are illustrated.

- **Chapter 5 Conclusion:** The thesis is finalized with conclusions in this chapter, and achievements and future recommendations are provided.

- **Appendix:** All other information which support this study and might help for future research has been attached here.

Chapter 2

Literature Review

2.1 Introduction

An earthquake is a natural phenomenon and does not always cause disaster. Only objects with potential weaknesses can turn the event into a catastrophe. This potential weakness known as the earthquake (seismic) risk, is related to the loss possibility through an earthquake occurrence. This probability is a combination of three variables: the earthquake hazard, the assets at risk, and the vulnerability of the assets [170]. The purpose of this chapter is to review available techniques used in the RC building vulnerability and earthquake risk assessment.

2.2 Earthquake and Seismic Risk

Thousands of earthquakes around the world occur every year; however, just a minimal extent is sufficiently able to be felt, and a very few cause considerable damage. Earthquakes can occur anywhere between the Earth's surface and about 700 kilometers below the surface, and its effect is decreased with increasing distance from the earthquake source [181]. The magnitude of the earthquake can be measured by computing the energy it releases during the event and is represented by a logarithmic scale [50]. Earthquakes were responsible for an estimated 1.87 million deaths in the 20^{th} century, with an average of 2,052 fatalities per event affecting humans between 1990 and 2010 [26]. Three significant earthquakes in Bhuj, India (7.9 M_S), El Salvador (7.6 M_S), and Arequipa, Peru, (8.4 M_S) resulted in at least 26,000 casualties in 2001; then in 2003 the Bam, Iran (6.6 M_S), with more than 26,000 deaths; and in 2004, Sumatra, Indian Ocean (9.3 M_S), resulted in a further 280,000 deaths; the Kashmir earthquake of October 8^{th}, 2005 caused over 85,000 casualties, the Java earthquake May 27^{th}, 2006 with 6000 people and Haiti earthquake January 12^{th}, 2010 caused more than 316,000 people to lose their lives [185]. Various reports and observations had concluded that most of the earthquake-related injuries result from structural collapses, and it is responsible for more than 75 percent of deaths in an earthquake during the past century [51].

In today's highly competitive world, occupants have a high propensity towards urban metropolitan cities that lead to rapid urbanization, ill-construction practices, and the additional impact of natural disasters raise the adverse effects on the economy [8]. Furthermore, the enormous risks due to natural hazards could be of great concern and therefore, in 2015 to configure the Disaster Risk Reduction (DRR), a unit of global leaders from the disaster management sector assembled together in Sendai, Japan [200], with the aim of defining a global strategy for the substantial reduction of disaster risk before 2030. The funding for the DRR initiatives prior to an event still remains significantly low in spite of the rising costs of disasters. [189].

The impact of earthquake phenomenon plays a vital role in aggravating different issues such as the economic wealth, damage to cultural and social environments, rising fatalities, harm to human lives, destruction of shelter, and diminishing livelihoods [8]. Rapidly developing urban cities, especially in the middle – income countries across the globe, seem more susceptible to the seismic risks caused by the vulnerability levels of structures in disastrous event scenarios [154]. Nevertheless, the future prediction of upcoming earthquake events and their scale of impact can be evaluated by seismic risk assessment methods. This process can be performed at different stages, such as urban, regional, and national levels, to assure the safety of society with the help of policymakers and disaster management experts [131]. Exceptionally intricate complexities can occur during a seismic risk assessment between the dynamic nexus between the city's built environment, citizens and to the existing networks [119, 28].

In practice, seismic risks could be reduced by introducing some advanced and beneficial policies that help to avoid the future risks, for public awareness, by the implementation of the policies based on land usage, seismic regulations with construction laws, for the amelioration of disaster response plans, strengthening the serving infrastructure, or the development of financial protection through insurance or household savings [201]. Nevertheless, the policy-making might be affected by actions taken under political scenarios, which typically overshadow the technical advice or warnings [183] due to the assortment of pressures. Even more, the presence of technical, institutional, and operational obstacles in the coordinated line of actions between the technical experts and decision-makers worsens the blend of problems, with additional difficulties in interpreting results, low salience, low technical capacity, and short political timescales. The controversy amongst them to improve political perceptions for releasing funds in disaster resilience domains, such as the yielding of a "triple dividend", where the co-benefits to minimizing the disaster losses would be highlighted, including enhancing to the general economy, social as well as for the development of surrounding environmental development [189, 29].

Decisions on how to wisely and effectively invest limited resources on the most beneficial or cost-effective strategies for seismic risk reduction [175, 100] rely on accurate risk assessments [126] and a full understanding of the scale of uncertainties associated. As with all modelling, seismic risk assessments have both epistemic [163] and aleatory uncertainties [158] accumulated from the data used as modelling inputs [32], and from the modelling approach [159]: communicating the scale of these methodological limitations and the impact on results is vital to ensure effective DRR decisions [131, 164]. Diverse attitudes to uncertainty and risk exist between DRR decisions makers, but when the financial benefits are apparent, these balance out significantly [59].

Potential losses from seismic hazards can be categorized by social, ecological, environmental factors. Estimating the financial losses for a target building stock requires the following structural parameters: 1- the ground shaking properties (hazard), 2- the inventory of buildings exposed to the ground shaking (exposure), and 3- the vulnerability of the buildings exposed for the expected ground shaking [194]. This process is inherently convoluted, but in its most basic form is presented in Figure 2.1 [61]: a substantial amount of data is needed for each box and collecting this is cumbersome and fraught with uncertainties, particularly when the study area is large and complex, as all cities are.

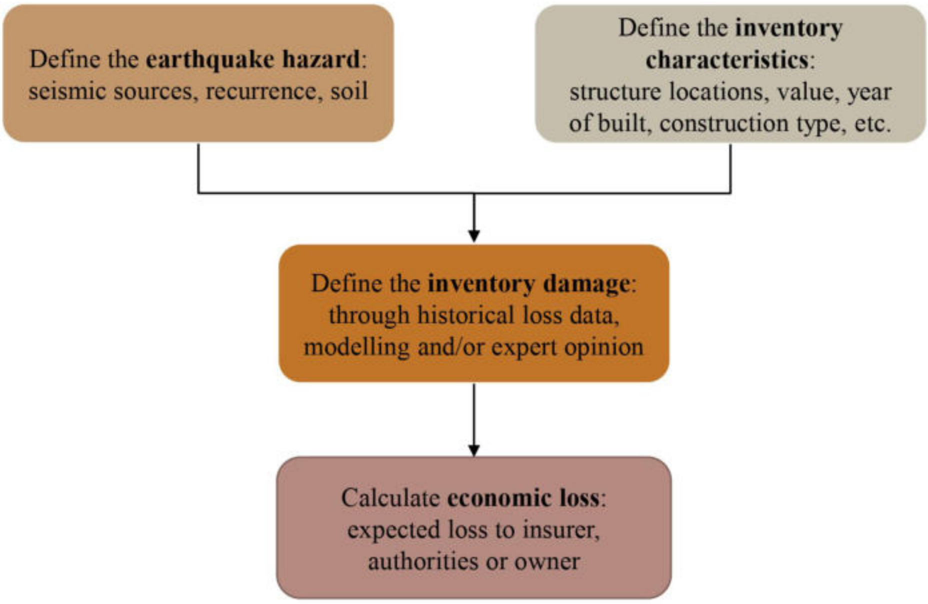


Figure 2.1: The process of seismic risk assessment (adapted from Grossi [61])

Uncertainty exists in all forms of modeling, and is rife in seismic risk assessment [133, 20] as it includes many imperfect inputs and employs imperfect modeling procedures. The uncertainty in the assessments accumulate from the primary components (seismic hazard, exposure, and vulnerability) [53], and are exacerbated by their combination. Despite widespread uncertainty, results rarely report or estimate it [161] notwithstanding recent advances in its quantification, particularly in the assessment of hazard [193, 158, 58] and, increasingly, vulnerability [27, 162, 118]. Studies on the uncertainty caused by the exposure component are lacking [53, 45], so this thesis aims to address part of this lacuna by investigating the uncertainty and overcoming it when assessing seismic vulnerability and risk.

The most efficient evaluation of seismic risk assessment is from a whole to part perspective. It is not a singular matter of technical examination, but additionally, has to be assessed in terms of its acceptability to public customs and various other aspects. In different circumstances, vulnerability is the probability of the in-service environment affected by virtue of hazard: higher the vulnerability, higher the likelihood of failures in seismic hazard scenarios. The significant damage caused to a building either as complete or parts that are consequential for physical stability in scenarios of intensive seismic excitation can be defined as structural vulnerability.

The prediction of damage by seismic ground motions at a specific intensity can be defined as building structure seismic vulnerability [31]. The level of damage predicted from the earthquake shall be directly correlated to structural vulnerability, yet contrary to the safety level of the building. High vulnerability depicts low safety and vice versa.

2.3 Procedures for Earthquake Vulnerability Assessment

In civil engineering, RC is one of the most commonly used building materials that play an important role in the structure of the building. Estimating the earthquake hazard of such buildings on an urban scale, as a critical element in any risk assessment, is an expensive, time-consuming and complicated task, especially in regions with moderate to high seismic hazard. The majority of existing buildings in these seismic regions do not satisfy modern design code requirements and need to be upgraded accordingly to an appropriate level. For instance, in Istanbul-Turkey as a high seismic area, around 90% of buildings are substandard, which can be generalized for other earthquake-prone regions in Turkey [186]. Therefore, it is essential to assess the seismic risk and vulnerability of buildings in urban areas as a primary parameter of the earthquake disaster management policy [68]. The term "seismic vulnerability" is defined as "the susceptibility of a population of buildings to undergo damage due to seismic ground motion" [11]. There are many methods available for seismic assessment of structures, which involve detailed structural analysis and design.

A three-stage assessment i.e. Tier 1, Tier 2 and Tier 3 procedures for seismic evaluation of existing buildings by considering the level of safety and enhancing detail analysis is proposed by FEMA 310 [3]. Tier 1 shall be described as a screening stage for prospective deficiencies, inadequacies and expected seismic behavior to recognize its compliance. Tier 2 is an evaluation process for the representation and study of the lateral-force-resisting system that performs restricted by basic linear and non-linear analysis techniques. Tier 3 is a comprehensive evaluation stage for structures expressing deficiencies identified in Tier 2 for advanced evaluation like finite element analysis. In general, based on their level of complexity, seismic vulnerability examination procedures are categorized into three types [179]:

1. Rapid Visual Screening (RVS) or Level 1 (Tier 1) procedure:

    - This stage shall suffice with visual inspection and subsequent additional parametric information for evaluation. This stage is also briefly named as walk-down evaluation. The procedure does not involve any complicated numerical computations from the user side. It is performed with the motive of identifying the primary concern levels of the structure with prioritizing the building for further detailed examination and classification of vulnerability and risk of buildings. The procedures in FEMA 154 [195], FEMA 310 Tier 1 [3], and the similar procedure adapted by Sucuoglu and Yazgan [186] are associated with this procedure.

2. Simplified Vulnerability Assessment (SVA) or Level 2 (Tier 2) procedure:

    - This procedure which is commonly known as preliminary assessment methodology (PAM) utilizes fundamental engineering logic and analysis for evaluation. This method engages the data inputs from the preliminary visual screening performed beforehand and structural archives or on-site measurements both for structural and nonstructural elements. The procedures by FEMA 310 Tier 2 [3], Yakut et al. [209] are illustrations of this tier.

3. Detailed Vulnerability Assessment (DVA) or Level 3 (Tier 3) procedure:

    - This procedure requires an in-depth comprehensive analysis (typically performed by using sophisticated computer software), which in analogy, is far more complicated that design for a new building. This method is generally advised to be performed for all consequential, heritage and emergency buildings. The procedures proposed in Ismail [81], FEMA 356 [40], and Park [149] are some examples of the third stage assessment procedures.

These detailed assessment methods consume more time and need more experts when the assessment must be performed for a large number of buildings [174]. To filter and prioritize the buildings for comprehensive, time- and resource-saving assessment, alternative Rapid Visual Screening (RVS) methods have been developed [87], which is the main focus of this thesis. Table

2.1 shows the different levels of vulnerability assessment, their required time, cost, and level of qualified persons. Figure 2.2 displays the different seismic vulnerability methods and highlights those interpreted in detail in this thesis, which will be discussed in the following.

Table 2.1: Different Levels of vulnerability assessment (adopted from [195, 83, 171, 128])

Vulnerability of undamaged buildings	**Tier1 (RVS)**	**Tier2 (Non-linear analysis)**	**Tier3 (Finite element)**
Time required	Minutes/Hours	Days	Weeks
Relative cost	$	$$$	$$$$
Qualifications	Properly trained people	Structural engineers experienced in seismic evaluation and design + instrument and experimental test	

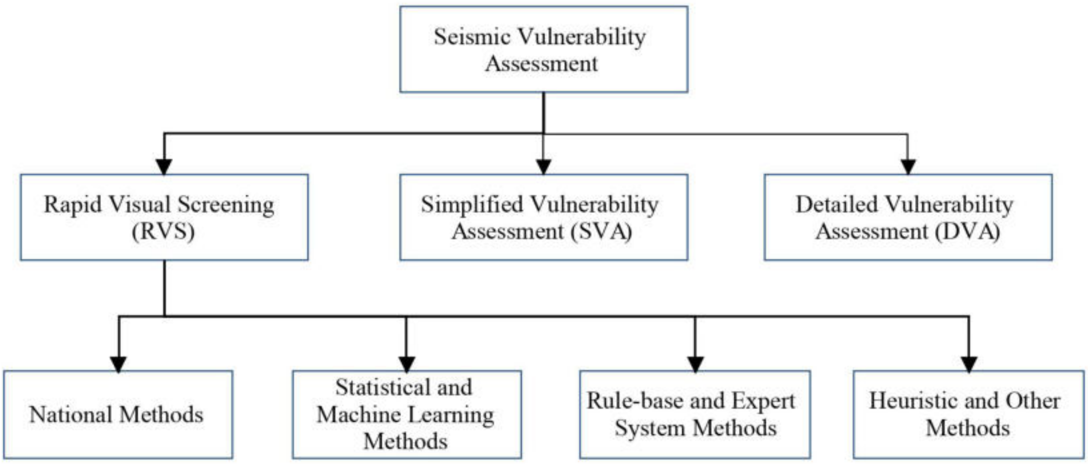


Figure 2.2: Different seismic vulnerability assessment methods

2.4 Rapid Visual Screening

Rapid Visual Screening (RVS) or Rapid Screening Procedure (RSP) is a deliberate method for the recognition of building's vulnerability by deciding which buildings are potentially dangerous. This method depends on the physical observation of the Building and does not need any detailed analysis. According to FEMA 154 [54] this method use functional vulnerability form for calculating the numeric scores for seismic vulnerability assessment of buildings. The main structural system associated with the lateral load-resisting mechanism is recognized by a scoring system. Some of the important building factors that shift the seismic performance is also considered as a modifying factor for the final score. Most of the evaluations begins by collecting information at site which provide an ease for the decisions makers. This method is proved to be very useful in prioritizing the buildings, and the regional seismicity factor showed a significant concern in seismic vulnerability scores of buildings. This procedure also saves time and resources that can be used effectively for the buildings that need detailed assessment. [55, 87, 83].

The first RVS methodology was proposed by the Federal Emergency Management Agency (FEMA), U.S.A in 1988 as "Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook" [55]. This assessment was based on a logarithmic relationship between the final score of the building to the probability of collapse, was complicated for non-experienced users to interpret, so an alternate non-logarithmic or linear format was proposed to ease the demand of decision-makers. Further, in 2002, from the effect of earthquake disasters in the 1990s, the methodology has been modified to integrate the latest technological advancements [206]. Many countries follow the same RVS methodology as of FEMA with relevant modifications with respect to their own region or country [87, 128].

RVS method was developed for a wide variety of users, it helped people in public sector as well as private sector, being an owner of a building it was easy to decide which buildings are seismically fit and which building needs further examination. The end-result from a RVS can further be implemented for a variety of applications as an important part of the earthquake disaster risk supervision program disclosed by Sinha and Goyal [179]:

- Identifying the building seismic vulnerability, if it is fit for usage or needs further evaluation.
- Ranking a city's or community's seismic rehabilitation needs.
- Preparing a plan for a society or a city about the supervision of seismic risk.
- Assessment regarding building's safety should be well planned during the post earthquake circumstances.
- Developing a system based on information and is connected to a seismic vulnerability of a specific building. This information system is further associated to regional rate and to make the building prior for re-development.
- A specific building must be acknowledged for further retrofitting to prevent collapse.
- Enhancing the perception among different people that are mostly concerned with the seismic vulnerability of buildings.

The "Rapid visual screening" method is very helpful in different parts of the world. It can be applied in both; urban areas as well as rural areas. Furthermore, the approach is mostly rely upon the engineering principles, urban infrastructure are more effective and applicable in contrast to the architecture in rural areas [66]. Since the framework of buildings in urban areas can easily be observed and examined. The architecture in rural areas are mainly concerned with domestic and functional rather than public or monumental buildings. Also most of them use local material and not in accordance to design codes. For this reason, rural buildings are less compatible for RVS application and the need of vulnerability assessment is very low or only need some adaptations [179].

2.5 Review on the Developed RVS Methods

RVS has been widely used in seismic countries as a practical and simple tool for evaluating the vulnerability of buildings. Therefore, this challenge is in the interest of many researchers and still is under development and improvement. The most common RVS methodologies that have been proposed worldwide are precisely described in the following.

2.5.1 National Methods

The most common RVS methodologies that have been provided by national technical codes are discussed in the following.

2.5.1.1 U.S.A. RVS (FEMA P-154)

As mentioned earlier, the RVS method for buildings by FEMA was first proposed in 1988 as FEMA 154 and further in 2002 it has been revised and the latest revision was in 2015 which is given as third edition and was named as FEMA P-154 [128]. In FEMA P-154 [55], the person performing the RVS procedure should fill a data collection form by conducting visual inspection of building from exterior, if possible interior during sidewalk survey. The data collection form will have space for all the necessary data of a building including pictures and sketches as presented in Figure 2.3. FEMA P-154 provided data forms for different levels of seismicity. Depending on the classification of seismicity, the relavent data form will be selected. The classification of levels of seismicity is based on the spectral response acceleration values as shown in Table 2.2.

Table 2.2: Range and Median MCE_R Spectral Response Acceleration Values in Each Seismic Region [55]

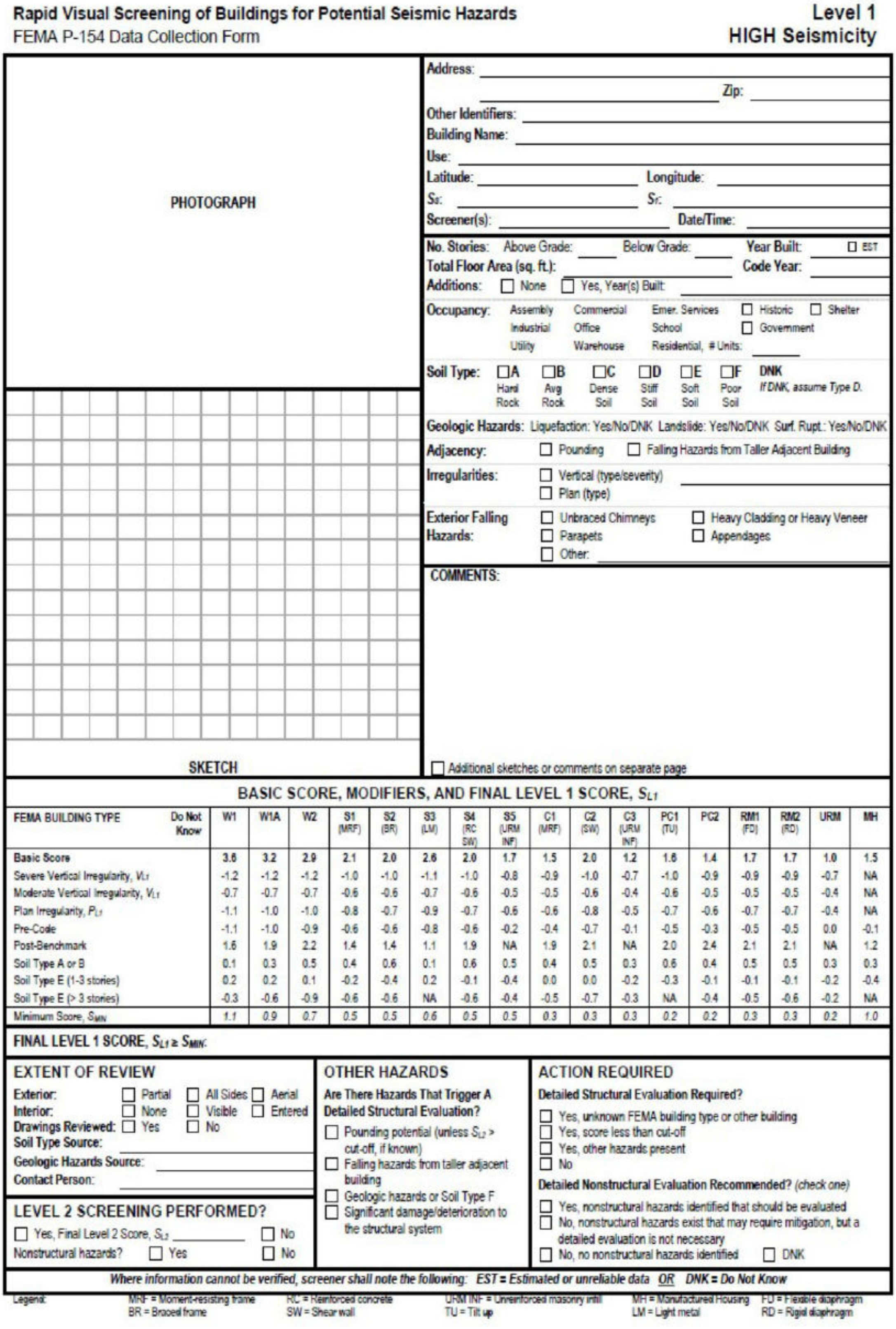
Seismicity Region	Range of response values for Each Region		Median Response values for Each Region	
	$S_s(g)$	$S_1(g)$	$S_{s,avg}(g)$	$S_{1,avg}(g)$
Low(L)	$S_s < 0.25g$	$S_1 < 0.1g$	0.2	0.08
Moderate (M)	$0.25g \leq S_s < 0.5g$	$0.1g \leq S_1 < 0.2g$	0.4	0.16
Moderately High (M)	$0.5g \leq S_s < 1g$	$0.2g \leq S_1 < 0.4g$	0.8	0.32
High (H)	$1g \leq S_s < 1.5g$	$0.4g \leq S_1 < 0.6g$	1.2	0.48
Very High (VH)	$S_s \geq 1.5g$	$S_1 \geq 0.6g$	2.25	0.9

Any data form can be filled in two parts. The first or top half of the part is to fill all the general information such as its address, location, use, year of construction etc. along with pictures and drawings of building. The second or bottom half of the form is provided with necessary scores for different parameters based on building type. All the parameters and the procedure of calculating final scores is explained in further sections.

The procedure starts with the selection of an appropriate basic score for the building, which is changed further by using score modifiers. The lower the score, the higher the vulnerability of the building [55]. The classification of damage based on Final Score is shown in Table 2.3.

Minimum Score, S_{MIN}: In some cases, the final score obtained can be zero or a negative number, which means a building is more than 100 percent damaged. To avoid this issue, FEMA P-154 provided the minimum score a building can have in the data collection form. The minimum score was developed by considering the worst possible combination of all score modifiers at once. If the final score is less than the minimum score provided in the data completion form, the minimum score will be taken as the final score.

Basic Score: The basic score of a building was provided based on building types classified by FEMA P-154. As the scope of this thesis is on the RC buildings therefore, structural system here are C1, C2 and C3. Figures 2.4 to Figure 2.6 illustrate the structural system of C1, C2 and C3, respectively. Here is the description of each structure system :



Rapid Visual Screening of Buildings for Potential Seismic Hazards
FEMA P-154 Data Collection Form

Level 1
HIGH Seismicity

PHOTOGRAPH

Address:
Zip:
Other Identifiers:
Building Name:
Use:
Latitude: Longitude:
S_S: S_1:
Screener(s): Date/Time:

No. Stories: Above Grade: Below Grade: Year Built: ☐ EST
Total Floor Area (sq. ft.): Code Year:
Additions: ☐ None ☐ Yes, Year(s) Built:

Occupancy: Assembly Commercial Emer. Services ☐ Historic ☐ Shelter
Industrial Office School ☐ Government
Utility Warehouse Residential, # Units:

Soil Type: ☐A Hard Rock ☐B Avg Rock ☐C Dense Soil ☐D Stiff Soil ☐E Soft Soil ☐F Poor Soil DNK *If DNK, assume Type D.*

Geologic Hazards: Liquefaction: Yes/No/DNK Landslide: Yes/No/DNK Surf. Rupt.: Yes/No/DNK

Adjacency: ☐ Pounding ☐ Falling Hazards from Taller Adjacent Building

Irregularities: ☐ Vertical (type/severity) ☐ Plan (type)

Exterior Falling Hazards: ☐ Unbraced Chimneys ☐ Heavy Cladding or Heavy Veneer ☐ Parapets ☐ Appendages ☐ Other:

COMMENTS:

SKETCH

☐ Additional sketches or comments on separate page

BASIC SCORE, MODIFIERS, AND FINAL LEVEL 1 SCORE, S_{L1}

FEMA BUILDING TYPE (Do Not Know)	W1	W1A	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	MH
Basic Score	3.6	3.2	2.9	2.1	2.0	2.6	2.0	1.7	1.5	2.0	1.2	1.6	1.4	1.7	1.7	1.0	1.5
Severe Vertical Irregularity, V_{L1}	-1.2	-1.2	-1.2	-1.0	-1.0	-1.1	-1.0	-0.8	-0.9	-1.0	-0.7	-1.0	-0.9	-0.9	-0.9	-0.7	NA
Moderate Vertical Irregularity, V_{L1}	-0.7	-0.7	-0.7	-0.6	-0.6	-0.7	-0.6	-0.5	-0.5	-0.6	-0.4	-0.6	-0.5	-0.5	-0.5	-0.4	NA
Plan Irregularity, P_{L1}	-1.1	-1.0	-1.0	-0.8	-0.7	-0.9	-0.7	-0.6	-0.6	-0.8	-0.5	-0.7	-0.6	-0.7	-0.7	-0.4	NA
Pre-Code	-1.1	-1.0	-0.9	-0.6	-0.6	-0.8	-0.6	-0.2	-0.4	-0.7	-0.1	-0.5	-0.3	-0.5	-0.5	0.0	-0.1
Post-Benchmark	1.6	1.9	2.2	1.4	1.4	1.1	1.9	NA	1.9	2.1	NA	2.0	2.4	2.1	2.1	NA	1.2
Soil Type A or B	0.1	0.3	0.5	0.4	0.6	0.1	0.6	0.5	0.4	0.5	0.3	0.6	0.4	0.5	0.5	0.3	0.3
Soil Type E (1-3 stories)	0.2	0.2	0.1	-0.2	-0.4	0.2	-0.1	-0.4	0.0	0.0	-0.2	-0.3	-0.1	-0.1	-0.1	-0.2	-0.4
Soil Type E (> 3 stories)	-0.3	-0.6	-0.9	-0.6	-0.6	NA	-0.6	-0.4	-0.5	-0.7	-0.3	NA	-0.4	-0.5	-0.6	-0.2	NA
Minimum Score, S_{MIN}	1.1	0.9	0.7	0.5	0.5	0.6	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.2	1.0

FINAL LEVEL 1 SCORE, $S_{L1} \geq S_{MIN}$:

EXTENT OF REVIEW
Exterior: ☐ Partial ☐ All Sides ☐ Aerial
Interior: ☐ None ☐ Visible ☐ Entered
Drawings Reviewed: ☐ Yes ☐ No
Soil Type Source:
Geologic Hazards Source:
Contact Person:

LEVEL 2 SCREENING PERFORMED?
☐ Yes, Final Level 2 Score, S_{L2} ☐ No
Nonstructural hazards? ☐ Yes ☐ No

OTHER HAZARDS
Are There Hazards That Trigger A Detailed Structural Evaluation?
☐ Pounding potential (unless S_{L2} > cut-off, if known)
☐ Falling hazards from taller adjacent building
☐ Geologic hazards or Soil Type F
☐ Significant damage/deterioration to the structural system

ACTION REQUIRED
Detailed Structural Evaluation Required?
☐ Yes, unknown FEMA building type or other building
☐ Yes, score less than cut-off
☐ Yes, other hazards present
☐ No
Detailed Nonstructural Evaluation Recommended? (check one)
☐ Yes, nonstructural hazards identified that should be evaluated
☐ No, nonstructural hazards exist that may require mitigation, but a detailed evaluation is not necessary
☐ No, no nonstructural hazards identified ☐ DNK

Where information cannot be verified, screener shall note the following: EST = Estimated or unreliable data OR DNK = Do Not Know

Legend: MRF = Moment-resisting frame; BR = Braced frame; RC = Reinforced concrete; SW = Shear wall; URM INF = Unreinforced masonry infill; TU = Tilt up; MH = Manufactured Housing; LM = Light metal; FD = Flexible diaphragm; RD = Rigid diaphragm

Figure 2.3: Data collection form of FEMA P-154 RVS methodology for High Seismicity[55]

Table 2.3: Structural Scores with Damage Potential [129]

Rapid Visual Screening Score	Damage Potential
$S < 0.3$	High probability of Grade 5 damage; Very high probability of Grade 4 damage
$0.3 < S < 0.7$	High probability of Grade 4 damage; Very high probability of Grade 3 damage
$0.7 < S < 2.0$	High probability of Grade 3 damage; Very high probability of Grade 2 damage
$2.0 < S < 2.5$	High probability of Grade 2 damage; Very high probability of Grade 1 damage
$S > 2.5$	Probability of Grade 1 damage

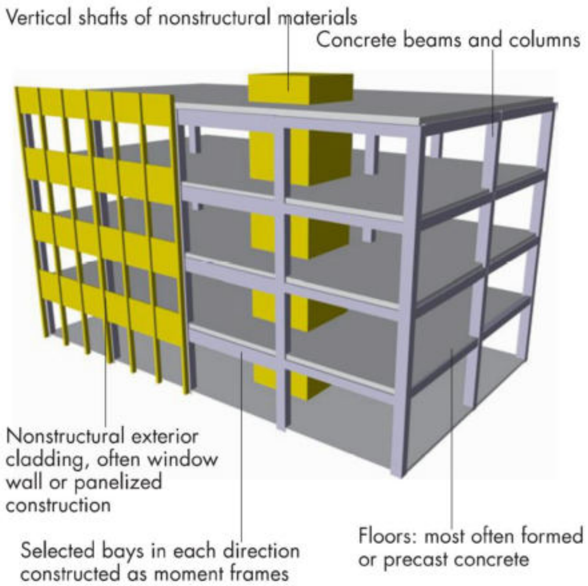


Figure 2.4: FEMA building type C1, concrete moment frames (adopted from [15])

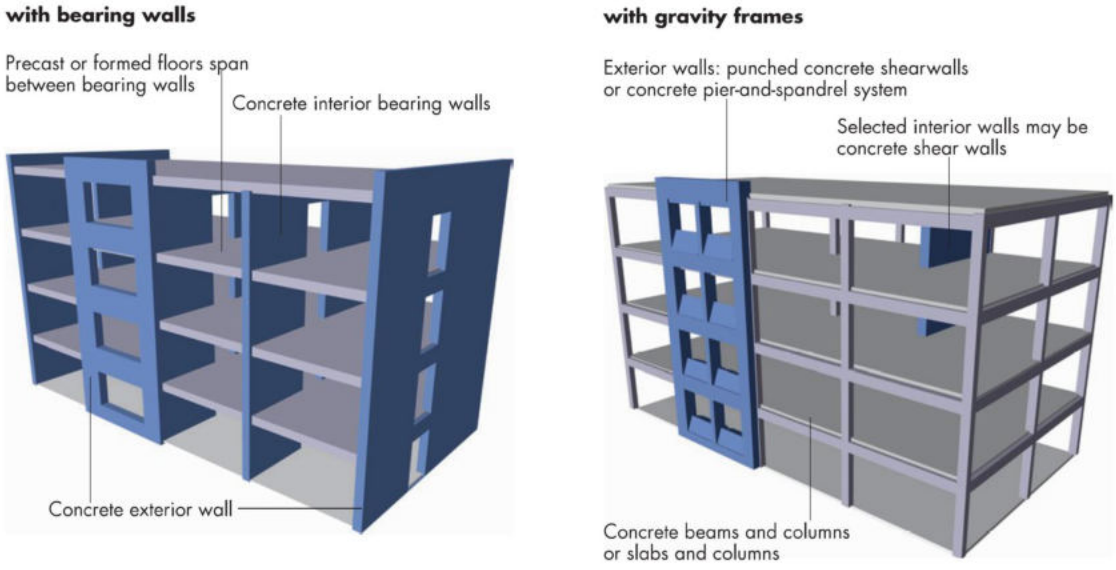


Figure 2.5: FEMA building type C2, concrete shear walls (adopted from [15])

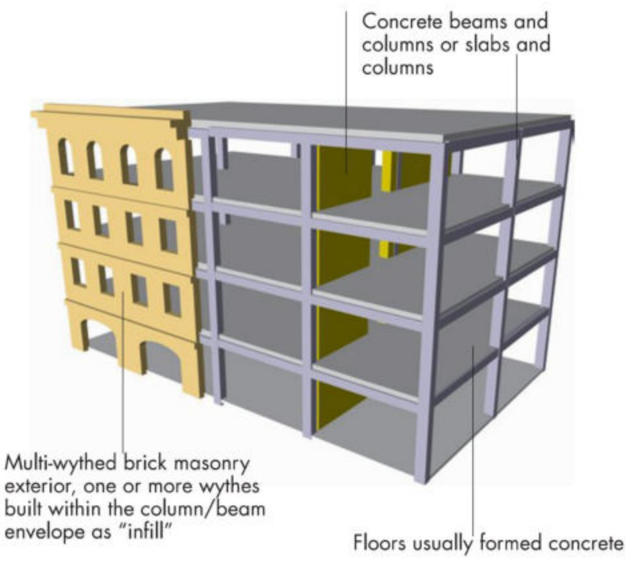


Figure 2.6: FEMA building type C3, concrete frames with infill masonry (adopted from [15])

- C1: concrete moment frames
- C2: concrete shear walls
- C3: concrete frames with infill masonry

Score modifiers are as below:

- Vertical irregularities: FEMA P-154 divided vertical irregularities into two parts: severe and moderate vertical irregularities. According to FEMA P-154, there is a total of seven vertical irregularities. Figure 2.7 presents different vertical irregularities that a building can have.
- Plan irregularities: There are five different plan irregularities defined by FEMA P-154. If one or more plan irregularities are observed, then this modifier should be considered. Figure 2.8 shows different type of plan irregularities.
- Pre-Code: This modifier should be considered if the building was constructed before the initial adoption and enforcement of seismic codes. For low seismic regions, this score modifier does not apply as it is included in the basic score itself.
- Post-Benchmark: If the building was constructed after the adoption and enforcement of significantly improved seismic codes by the local jurisdiction, this modifier should be applied. For both pre-code and post-benchmark modifiers, the year of implementation of seismic codes for the first time and the year in which the seismic codes improved (benchmark year) of the region should be known beforehand.
- Soil Type: Different score modifiers are provided based on the type of soil. Data collection forms have soil modifiers only for soil type A, B, and E; while the basic score was calculated assuming the average of soil type C and D. Also, there is no Score Modifier for Soil Type F because buildings on Soil Type F cannot be screened adequately with the RVS procedure. If the building is located on Soil Type F, it should be considered as "Geologic hazards" and a detailed structural evaluation is necessary.

From the below Equation the final score for FEMA P-154 will be calculated:

$$F_{FEMA} = BS + VI + PI + PC \text{ or } PB + S_{AB} \text{ or } S_E \tag{2.1}$$

Where BS is basic score, VI and PI are vertical and plan irregularities, respectively. PC is pre-code and PB is post benchmark while soil type is S_{AB} or S_E.

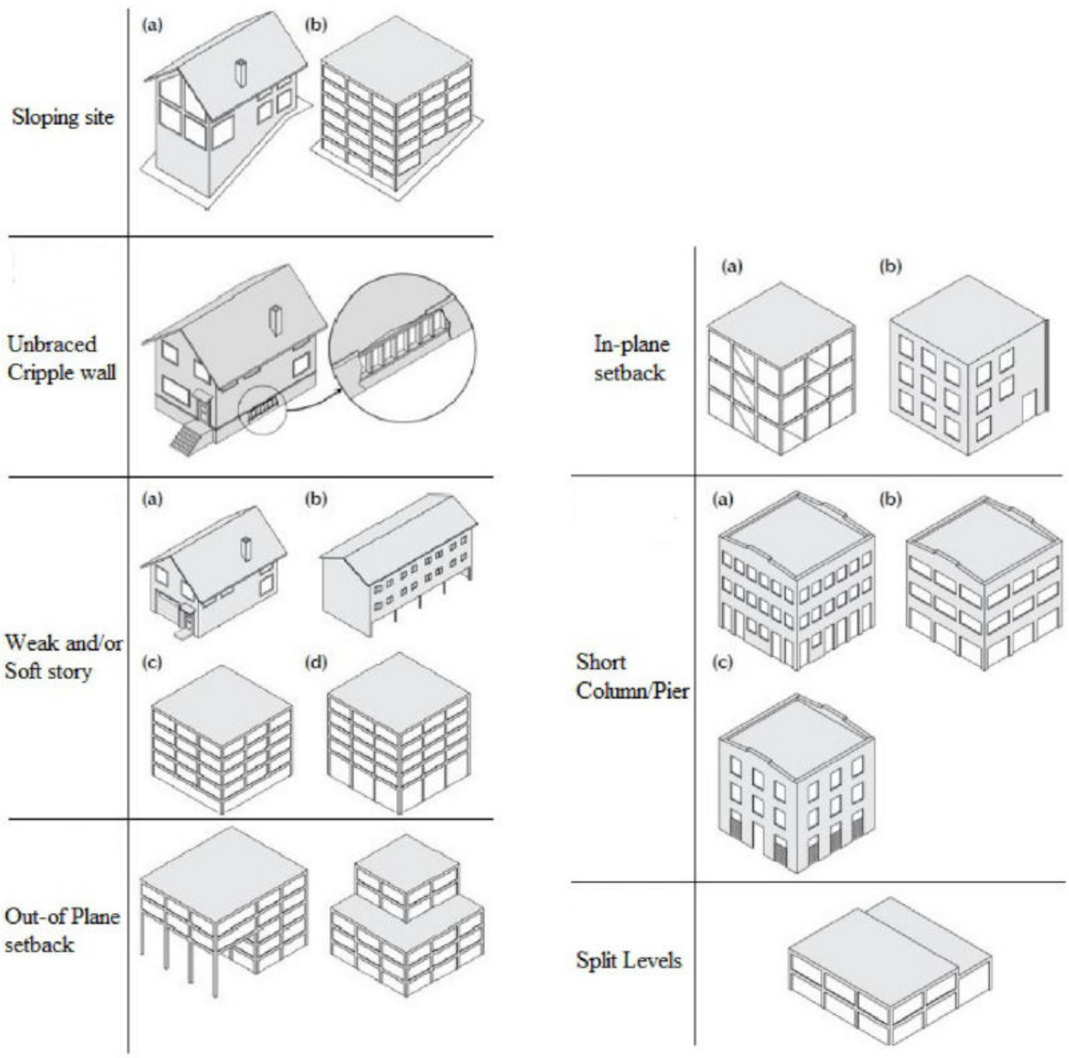


Figure 2.7: Vertical irregularities according to FEMA P-154 [55]

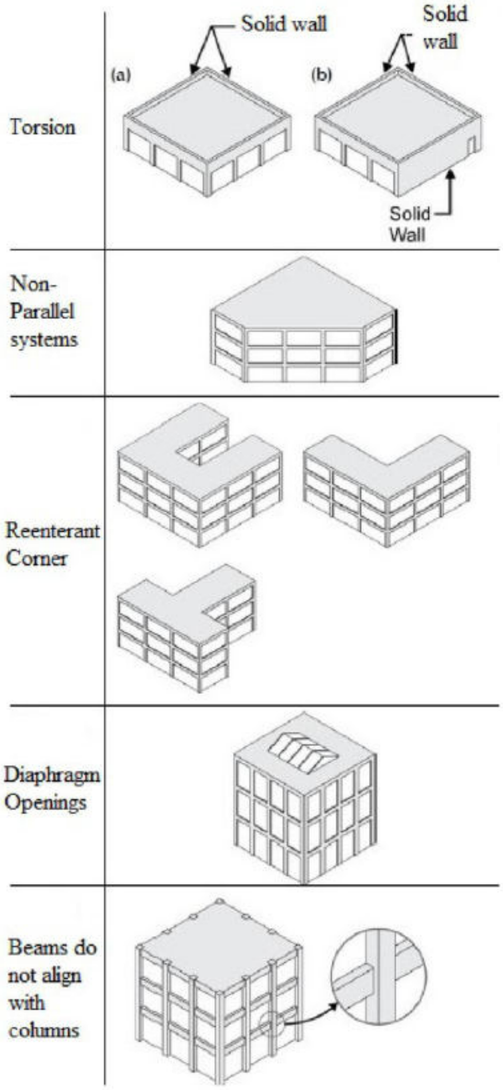


Figure 2.8: Plan irregularities according to FEMA P-154 [55]

2.5.1.2 Indian RVS (IITK-GSDMA)

An RVS methodology has been developed based on FEMA 154 by the Indian Institute of Technology, Kanpur (IITK), with the support of the Gujarat State Disaster Mitigation Authority (GSDMA) in "Seismic Evaluation and Strengthening of Existing Buildings" [156]. It was promoted by completing proper modifications to FEMA 154, considering Indian conditions. These adjustments include only the values of scores and parameters, but the calculation procedure is similar to FEMA 154 and FEMA P-154. Indian RVS uses a similar data collection form as that of FEMA 154 with space to write all the important information of the building and extra space for photos and plan of the building and has different data collection forms for various seismic zones [1]. The classification of seismic zones is shown in Table 2.4 [1].

Data forms provide different basic scores for different building types classified based on the moment-resisting system and the classification given in the data collection form itself [178].

Score modifiers are as follow:

- Mid-Rise and High-Rise: Depending on the number of stories, either of these modifiers should be selected. If the number of stories is between four and seven, inclusive, then

Table 2.4: Seismic zone classification according to IS 1893:2002(Part 1)[1]

Seismic Zone	Seismic Hazard Level
Zone II	Low seismic hazard (maximum damage during earthquake may be up to MSK intensity VI)
Zone III	Moderate seismic hazard (maximum damage during earthquake may be up to MSK intensity VII)
Zone IV	High seismic hazard (maximum damage during earthquake may be up to MSK intensity VIII)
Zone V	Very high seismic hazard (maximum damage during earthquake may be of MSK intensity IX or greater)

mid-rise modifiers should be selected. If it is more than seven, then high-rise modifiers should be considered. If the number of stories is less than four, there is no need to consider these modifiers.

- Vertical irregularity: If any of the irregularities, such as steps in elevation view, inclined walls, buildings on a hill, soft story, buildings with short columns, and unbraced crippled walls are identified, then this modifier should be considered.
- Plan irregularity: This modifier should be considered when any of the irregularities, like buildings with re-entrant corners (L, T, U, E, + shape) and buildings with different lateral resistance in both directions, have been observed.
- Code detailing: This modifier can be taken into account if the building was constructed after the adoption and enforcement of significantly improved seismic codes by the local jurisdiction.
- Soil type: Depending on the soil type, the respective score modifier should be applied. If the soil is liquefiable, then the Liquefaction modifier must be considered. The classification of soil types is based on Indian code [1].

By summing all the necessary modifiers to the basic score, the final score is determined, which can be used to classify the buildings into different damage categories, as it is stated at the bottom of the data collection form. In both FEMA P-154 and IITK GSDMA RVS methods, negative modifiers indicate that the value should be subtracted from the basic score. Hence, while adding modifiers to the basic score, it must be added along with a negative sign.

2.5.1.3 Turkish RVS (EMPI)

The Turkish RVS methodology [14] was formed by surveying buildings in Istanbul and is called the Earthquake Master Plan for Istanbul (EMPI), which can also be used for other parts of the country. EMPI contributed different RVS methods for different types of construction, which in this study, the method for RC buildings with 1–7 stories has been selected. First stage of assessment for 1–7 story RC buildings provides different primary scores (basic score) for buildings depending on Peak Ground Velocity (PGV) and the number of stories. Furthermore, this basic score might be modified by considering the vulnerability scores of necessary vulnerability parameters observed.

Initial score parameters are considering:

- Number of stories: Seismic force has a positive linear relationship with the number of stories of a building. Different basic scores are given to different numbers of stories.
- Local soil conditions: Depending on soil type, the intensity of ground motion changes. EMPI classified intensities into 3 zones based on PGV with Zone I as high intensity and Zone III as low intensity zones, as shown in Table 2.5. Depending on the number of stories and intensity zone, a basic score should be selected from Table 2.6 [14].

Table 2.5: Seismic zone classification in the Earthquake Master Plan for Istanbul (EMPI) [14].

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

Vulnerability parameters (Score modifiers) are including:

- Soft story: If the strength and stiffness of upper stories are more than that of the ground story, then it would be considered as a soft story. This effect happens mostly by providing more working areas on the ground floor for stores, shops, or parking purposes without constructing walls between the columns.
- Heavy overhangs: A few multi-story buildings might have extra overhangs, without any support, acting as a cantilever to main structural elements.
- Apparent building quality: The quality of a building also plays a role in the seismic resistance of the building. It depends on the materials used and the workmanship quality in construction. It is difficult to estimate the quality of a building solely by visual inspection, but a well trained and experienced person can estimate the quality of the building. EMPI classified building quality as good, moderate, and miserable.
- Short column: Semi infill frames, windows of partially buried basements, or mid-story beams lead to short columns. During an earthquake, this takes more damage because of high shear forces. It can be identified easily through visual inspection.
- Pounding effect: During an earthquake, adjacent buildings without enough space between them pound each other because of having different vibration periods. This effect usually is observed more in higher stories.
- Topographic effect: Foundations of buildings located on sloping grounds may not function properly because the seismic forces from the building cannot be transferred uniformly to the ground, resulting in a higher intensity of damage.

All the vulnerability parameters explained above should be considered appropriately depending on visual inspection and should be multiplied with vulnerability scores shown in Table 2.6. The vulnerability parameter values are shown in Table 2.7. The final score or Performance Score (PS) is calculated as follows:

$$PS = (\text{Basic Score}) - \sum (\text{Vulnerability Parameter}) \times (\text{Vulnerability Score}) \tag{2.2}$$

Table 2.6: Initial and vulnerability scores for concrete buildings given in EMPI [14].

Story No.	Zone I	Zone II	Zone III	Soft Story	Heavy Over-hang	Apparent Quality	Short Col-umn	Pounding	Topographic Effects
1, 2	90	125	160	0	−5	−5	−5	0	0
3	90	125	160	−10	−10	−10	−5	−2	0
4	80	100	130	−15	−10	−10	−5	−3	−2
5	80	90	115	−15	−15	−15	−5	−3	−2
6, 7	70	80	95	20	−15	−15	−5	−3	−2

Table 2.7: Vulnerability parameters in EMPI [14].

Soft story	No (0); Yes (1)
Heavy overhangs	No (0); Yes (1)
Apparent quality	Good (0); Moderate (1); Poor (2)
Short columns	No (0); Yes (1)
Pounding effect	No (0); Yes (1)
Topographic effect	No (0); Yes (1)

2.5.1.4 New Zealand RVS (NZSEE)

The document from the New Zealand Society for Earthquake Engineering (NZSEE) is a draft code that was proposed in 1996, based on visual screening method process presented in FEMA 154. The method works from external screening of the building and continued with further structural assessment inside building by performing detailed examination if required. This code renewed by NZSEE 2006 which recommends a two-stage seismic performance evaluation of buildings [138]. The Initial Evaluation Procedure (IEP) involves making an initial assessment of performance of existing buildings against the standard required for a new building, which is defined as "percentage new building standard ($\%NBS$)". A $\%NBS$ of 33 or less shows that the building is potentially earthquake prone according to the Building Act and needs more detailed evaluation [83]. The requirement of earthquake engineers process to yield quality results on this process is necessary.

2.5.1.5 Canadian RVS (NRCC 1993)

The method suggested by National Research Council, Canada (NRCC 1993) [137] is based on a Seismic Priority Index (SPI) which accounts for structural as well as non-structural factors including soil conditions, building occupancy, building importance, falling hazards to life safety, a factor based on occupied density, and the duration of occupancy [182].

2.5.1.6 European RVS (Euro Code 8)

The European method [33] is in the eurocode series of European standards (EN) related to construction, Eurocode 8: Design of structures for earthquake resistance. It was approved by the European Committee for Standardization (CEN). This method is the confirmation of the seismic resistance of an existing building damaged or not damaged by the effect of non-seismic and seismic actions, during the period of its particular useful life and its usability. Exams and redesign of existing structures can be carried out to modify the building based on safety factors [155].

2.5.1.7 Italian RVS (GNDT)

Vulnerability index method developed by National Earthquake Defense Group (GNDT) of Italy [13] is a score methodology based on eleven building parameters. The eleven parameters are resisting system type and organization, resisting system quality, conventional resistance, location and soil condition, diaphragms, plan configuration, vertical configuration, connectivity between elements, low ductility structural members, non-structural elements and preservation state. The Italian Vulnerability Index Method provides a detailed description of the building's seismic deficiencies that can be used to relate to equivalent building analysis models for damage estimation [128].

2.5.1.8 Greek RVS (OASP)

The Greek method was developed in 2000 by OASP (Earthquake planning and protection organization) [151], which is based on the first edition of the FEMA 154 Handbook. This method classifies buildings into one of 18 structural types based on the primary structural lateral load resisting system and structural materials of the building. Like FEMA 154, this method provides initial score to buildings based on its structural types, and later this score will be modified using modifiers. The modifiers used in this method, such as seismic zone, weak story, short column, and regular arrangement of masonry, gives the Basic Structural Hazard Score. Further, this score will be modified by using modifiers related to performance attributes to obtain the Final Score. Buildings with a final score of 2 or less will be investigated further. Greek method provided two scoring procedures to find potentially hazardous buildings with more accuracy. One is based on the first edition of FEMA 154, and the other one is based on the second edition of FEMA 154.

2.5.1.9 Japanese RVS (JPDPA 2001)

The Japanese Building Disaster Prevention Association (JPDPA) [85] developed a seismic index-based method for the entire earthquake resilience of a story that is estimated as the product of a basic seismic index based on strength and ductility index, an irregularity index and a time index. Japanese residential building inventory database has been compiled at the city/ward level by using following parameters: construction material, occupancy, height, and year of construction. Therefore, structural seismic capacity index I_s of a structure is expressed as a product of the Structural index, E_0, Configuration index, S_D and Age index, T:

$$I_s = E_0 \times S_D \times T \tag{2.3}$$

The seismic vulnerability of a story is assessed by structural seismic capacity index I_s and lateral load capacity index q. As shown in the Table , the structure may be considered to be safe when structural seismic capacity indices I_s of every story are greater than 0.6 and the lateral force capacity indices q of every story are greater than 1.0

Table 2.8: Vulnerability based on Japanese RVS [85]

Structural seismic capacity index (I_s) and lateral force capacity index q	Vulnerability assessment
$I_s < 0.3$ and $q < 0.5$	Likely to collapse
Others	Possible to collapse
$I_s \geq 0.6$ and $q \geq 1.0$	Unlikely to collapse

2.5.1.10 Thai RVS

Thailand also developed a rapid assessment framework by modification of FEMA 154 for their RVS method for determining probable seismic hazards by considering additional parts of building [97].

2.5.1.11 The Philippines RVS

Philippine RVS [197] follows the instructions of FEMA 154, but the final score evaluation has been modified and use slightly different quantification "cut off" technique for low, medium, and high risk by certain points. If FEMA 154 using 0-4 for the final score with 2 as cut off by means under 2 is unacceptable grade, the Philippine RVS defines risks by the S scores as shown in the Table 2.9.

Table 2.9: Vulnerability based on the Philippines RVS [197]

Risk of structure	S score
High risk	$S > 2$
Medium risk	$1 < S < 2$
Low risk	$S < 0.9$

2.5.1.12 Summary

A review by Nanda [128] figured out that, most of the developed methods like Canada, New zealand and Italy have not considered weak story and effective mass in RVS procedure and also Japanese and Italian procedures are based on very few parameters and lack clarity regarding ranking of buildings based on a scoring system. The European method requires a higher level of understanding as it requires a detailed structural analysis of the buildings and is a time consuming process. The Canadian Method may be used to classify the building in an inventory that complies with the National Building Code of Canada and is not suitable for use in other countries. A study by Harirchian [71] indicates that FEMA P-154 uses safety factors more than necessary and overestimate the level of risk for places with below-average ground motions [212]. Also in their study they recommended to use Indian and Turkish RVS in their local conditions as it is modified and calibrated for those regions and building types.

Some procedures for RVS have been proposed by several countries following the original method release by U.S.A. RVS (FEMA 154). The RVS of Turkey, India, Japan, the Philippine, and other countries are slightly different in method and scoring system compare to U.S.A. RVS though the general procedure itself is similar. This difference in RVS is a result of the local consideration, including seismicity conditions and building practice in the area. Score can be meaningful as explanation of percentage of expected damaged building (as in FEMA 154), as a level to position the vulnerability itself by certain groups like Indian RVS is based on European Macroseismic Scale 1998 (EMS-98), as a result of basic structural computation value in particular seismic zone (Turkish RVS), or just as a simple score for low, medium and high by certain points (e.g. Philippine RVS and others).

Using the RVS procedure has advantages and opportunities since it minimizes the complicated examination, and the application is simple and widely open for public use. Before going to a higher level of examination, this first judgment is meaningful for building categorization since the main structural system, and building irregularities that modify the seismic performance are identified. However, the RVS examination itself is not for global building. It needs the local consideration regarding seismicity and building technique in the area need to be assessed. It also needs to follow technological development for updating the tools. For this reason, RVS method is still widely open subject to be discussed.

2.5.2 Methods Based on Statistical and Machine Learning Techniques

Various statistical approaches have been adopted to develop an optimum correlation between the predictor variables (seismic parameters) and the damage states (output variables). Different researchers focus on various different seismic parameters and different statistical methods. Some of these methods have been concisely described in the following.

2.5.2.1 Multiple Linear Regression and Statistical Analysis

Linear regression is a function to have a prediction about one variable (dependent variable) depending on the provided information by another variable (independent variable). The Multiple Linear Regression (MLR) analysis is an extension of Ordinary Least Squares (OLS) regression [95], and it is a well-known method to be applied into RVS and model a linear relationship between the performance modifiers and the damage states of buildings that follows the below equation [196]:

$$y_i = \beta_0 + \beta_1 x_{i1} + ... + \beta_p x_{ip} + \epsilon, \tag{2.4}$$

where, for $i = 1, ..., n$ observations:
y_i = dependent variable,
x_{ij} = independent variable,
β_0 = y-intercept (constant term),
β_p = slope coefficients for each explanatory variables,
ϵ = the model's error term (also known as residuals).

A study by Ningthoujam and Nanda [135] shows the statistical regression analysis can be used as a preliminary assessment technique for the identification of most vulnerable buildings during an earthquake. The main task of this method was to draw a relationship between the explanatory variable of a building during an earthquake, and the outcome variables (different damages grades).

A case study of 396 damaged buildings was carried out after the Manipur earthquake (2016) in India using multiple regression analysis. The most important parameters responsible for analyzing the vulnerability of buildings during an earthquake are type of soil, apparent construction quality, age of the building, substantial overhang, maintenance condition, and number of stories as shown in the Table 2.10. The parameters analyzed during the multiple regression analysis were, soft story, re-entrant corners, age of building, apparent construction quality, asymmetry of staircase location, maintenance condition, type of soil, number of stories, substantial overhang, and floating columns. These parameters are taken to be predictor or independent variables. The damaged buildings during the earthquake were divided into five grades according to the damage grade definition of IS 1893. These grades were used as outcome variables or dependent variables. Grade 1 shows slight damage, Grade 2 shows moderate damage, Grade 3 shows heavy damage, Grade 4 shows destruction, and Grade 5 shows total damage.

The first selected independent variables were able to present around 60% of the variation in damage grades by regression analysis [95]. The damage grade of the buildings was further analyzed by a stepwise regression, which shows that out of the ten variables defined by the multiple regression, only six variables are responsible significantly for the damage grade of a building. These six independent variables are soil type, apparent construction quality, maintenance condition, the age of the building, substantial overhang, and the number of stories. The final score from the statistical analysis is compared with the physical observation by a survey of the building, and it was matched up to 64.65%, which shows the model to be highly accurate for seismic vulnerability assessment of existing buildings. Their proposed regression model is as below:

$$Y = 2.87+0.02X_1+0.12X_2+1.08X_3+0.65X_4-2.42X_5+0.03X_6+0.48X_7-0.11X_8+0.22X_9-0.30X_{10}. \tag{2.5}$$

Table 2.10: Predictor variables and assigned scores according to Ningthoujam and Nanda [135]

Sl.No.	Predictor variable	Type	Measurement
1	Age of building (X_1)	Quantitative	Number of years (1, 2, 3,...)
2	Number of storey (X_2)	Quantitative	Number of storey (1, 2, 3,...)
3	Apparent construction quality (X_3)	Ordinal	Good = 0, Moderate = 0.5, Poor = 1
4	Maintenance conditions (X_4)	Ordinal	Good = 0, Moderate = 0.5, Poor = 1
5	Type of soil (X_5)	Ordinal	Poor = 0, Medium = 0.5, Hard = 1
6	Soft storey (X_6)	Dummy	Present = 1, Absent = 0
7	Substantial overhang (X_7)	Dummy	Present = 1, Absent = 0
8	Floating column (X_8)	Dummy	Present = 1, Absent = 0
9	Re-entrant corners (X_9)	Dummy	Present = 1, Absent = 0
10	Asymmetry of staircase location with respect to plan (X_{10})	Dummy	Present 1, Absent = 0

Ozcebe et al. [142, 145] developed a method associated with a capacity index and demand index. All the calculations are based on the size, material properties, and orientation of the integrals consist of lateral loads of structural systems. Data used in this procedure had collected from the damage surveys after the earthquakes that occurred in Turkey. Several existed procedures helped to compile the data and use it for the proposed approach. A statistical approach is used to determine the capacity index and demand index of a building; it is then further divided into two categories, namely; immediate occupancy and life safety, depending upon their performance score. Furthermore, a building is considered to be structurally safe for usage if the capacity index is higher for both immediate occupancy and life safety than the demand index. If the demand index is higher for both immediate occupancy and life safety, than the building is considered to be unsafe or may be placed in a gray zone. The Methods associated with life safety only considers the first part, "Life safety" to be evaluated. The other two methods only provide the results of one parameter, which is not enough for evaluation; for analogy, the capacity index is subtracted from the demand index to minimize the outcome into a solo parameter. The value of this parameter is directly associated with the safety level of the building. Any hike in the value of this parameter also increases the safety level. The ratio of the capacity index over the demand index is observed to be more acceptable in the initial stage, but later on, it was renounced as mathematically unstable due to the variations in result.

The capacity index of a building depends upon several parameters, these parameters are, column's effective area, shear walls and column walls moment of inertia, difference between ground and upper story height , continuity of the load carrying frames, overhang amount at the building,shear walls and infill walls at ground story based on their larger dimension and number of stories. The demand index depends on the soil conditions based on shear wave velocity, distance to the fault and number of stories in the building. Therefore, the required data are the dimensions of the columns, shear wall and infill walls at the ground story, continuity of the frames, ground and upper story height, area of overhang portions, shear wave velocity, distance to the fault and number of stories. The drawback of this approach was, that it only restrained to turkey. It included all the secondary factors which were not certainly defined in the previous methods. The factors which were included are the presence of irregularities, regional seismicity, soil type, and quality of construction.

Jain et al. [83] developed a RVS method based on the data from the Bhuj earthquake in Ahmedabad, India, which occurred on 26 January, 2001. A team of researchers from Center for Environmental Planning and Technology (CEPT) university, observed approximately 6670 buildings including RC-frame, load-bearing masonry, and load-bearing wooden frame buildings that damaged during the earthquake. A sample of 270 RC-frame buildings were selected in their study that were affected within the scale of G_0 as no damage to G_5 as collapse. Generally, different vulnerability score modifiers are used that are easy to collect from the observational survey, such as the number of stories, presence of basements, quality of maintenance, re-entrant corners, open stories, and short columns. It was taken into account to assign performance scores for building usage, seismic zone, and soil condition as shown in Table 2.11. To develop Expected Performance Scores (EPS), they have performed statistical analysis on their data, and it has been compared with the Observed Performance Scores (OPS) where was assigned for the 5 damage groups. Later, the significant parameters have been investigated by their proposed methods, and some of them with negligible effect have been dismissed, for instance X_3 and X_6 [95]. The proposed EPS based on a multilinear regression model is as below:

$$EPS = A + C_0X_0 + C_1X_1 + C_2X_2 + C_4X_4 + C_5X_5 + C_7X_7, \tag{2.6}$$

where, C_i is the parameters estimates from 1000 bootstrap samples and therefore the following model for EPS calculation is proposed by

$$EPS = 85 + 10X_0 + 10X_1 - 20X_2 - 10X_4 - 10X_5 - 10X_7. \tag{2.7}$$

Table 2.11: Vulnerability parameters and assigned scores according to Jain et al. [83]

Parameter	**Title**	**Score**
X_0	Basement	Absent = 0, Present = 1
X_1	Number of stories	(N≤5) = 0, (N>5) =1
X_2	Maintenance	Good = 0, Moderate = 0.5, Poor = 1
X_3	Staircase asymmetry with respect to plan	Absent = 0, Present = 1
X_4	Re-entrant corners	Absent = 0, Present = 1
X_5	Open Story	Absent = 0, Present = 1
X_6	Stub columns	Absent = 0, Present = 1
X_7	Short columns	Absent = 0, Present = 1

Their proposed model figured 46% correctness of the combined sample while incorrectness with one level were for 88% of the buildings. According to this statistical analysis, taller buildings are more vulnerable to damage as compared to short height building.

Özhendekci et al. [147] followed the work by Jain [83] and proposed a method that an initial (basic) performance score is assigned to each building. The vulnerability parameters and damage conditions are predefined and an MLR analysis is carried out for an optimal scenario. A coded MATLAB script was used to select the best possible regression analysis from a possible regression model and the evaluation was carried out using the p-value method [95].

In the proposed RVS by Yakut et al. [209, 210], which is based on discriminant analysis, the damage classification considered six structural parameters such as number of stories (N), minimum normalized lateral stiffness index (MNLSTFI), minimum normalized lateral strength index (MNLSI), normalized redundancy score (NRS), soft story index (SSI), and overhang ratio (OR) [95].

They assumed that all buildings involved in the inventory are exposed to a particular earthquake; therefore, the damage is only assessed on the basis of structural parameters. In other words, the damage is evaluated merely based on the structural responses and not taking into account the excitation factors [73]. Regarding the characteristics of the damaged structures and the enormous number of the existing building stock, they proposed the following parameters, which are selected as the basic estimation parameters for this study too. A detailed description and a full discussion of the effect of these factors on the observed damage are given elsewhere [209, 213, 211].

The damage states have been reduced from five to three including none, and minor damage states, which were assigned to a category (N + L), a moderate damage level as (M), and severe damage and collapse states were as (S + C). Buildings that are damaged severely or collapsed would be classified as a member of the group (S + C) in the LSPC (Life Safety Performance Classification). Similarly, buildings might be grouped in any of none, minor, or moderate damage. The main goal of evaluating structures with this damage is to occupy buildings immediately after an earthquake. This group is therefore referred to as IOPC (Immediate Occupancy Performance Classification) [95].

Number of story is the total number of individual floor systems above the ground level. A study by Sucuoğlu et al. [186] noticed a clear indication that the number of stories is a very significant or perhaps the most dominant parameter in determining the seismic vulnerability of typical multistory concrete buildings in Turkey. Moreover, this parameter has a direct effect to natural time period of a building (T) [191] and can be computed for a concrete frame building or a shear wall building by using the expressions given below [166], where H is the height of the building and related to the number of stories:

$$T = 0.075(H)^{3/4} \text{ concrete frame building} \tag{2.8}$$

$$T = 0.05(H)^{3/4} \text{ shear wall building} \tag{2.9}$$

The redundancy indicates the degree of continuity of several frame lines to distribute the lateral forces throughout the structure system. The Normalized Redundancy Ratio (NRR) of a frame structure is calculated using Eq.2.10, where A_{tr} is the tributary area for a typical column, nf_x and nf_y are number of continuous frame lines in the critical story in x and y directions and A_{gf} is the area of the ground story. From the value of NRR, the following values on Table 2.12 are assigned to the NRS:

$$NRR = \frac{A_{tr}(nf_x - 1)(nf_y - 1)}{A_{gf}}. \tag{2.10}$$

Table 2.12: NRS Value Based on NRR

NRS	NRR
1	$0 \leq$ NRR ≤ 0.5
2	$0.5 \leq$ NRR ≤ 1.0
3	$1.0 <$ NRR

Damage and collapse due to the soft story are most often observed in buildings while the lower level containing the concrete columns behaved as a soft story in that the columns were unable to provide adequate shear resistance during the earthquake [76]. The ground story usually has fewer partitions than the upper story, which is also one of the main reasons for soft stories. Soft story index is defined as the ratio of the height of first story (i.e., the ground story), H_1, to the height of the second story, H_2:

$$SSI = \frac{H_1}{H_2}. \tag{2.11}$$

The existence of overhangs and balconies shifts the mass center of the building upward and thus, increase seismic forces and overturning moments. Based on different studies [48, 79], it was observed that buildings with overhangs were damaged more severe damages compared to regular buildings. This fact can attract researchers to choose a case study in Turkey, where 70 to 80% of buildings have overhangs [48]. Since overhangs make load calculation of a building more complicated and decrease earthquake strength of the structure, therefore it is recommended to prevent constructing overhangs; otherwise, this will increase the earthquake effects [144].

The area beyond the outermost frame lines on all sides of a floor plan is defined as the overhang area. The summation of the overhang area of each story, A_{ova}, divided by the area of the ground story, A_{gf}, is defined as the overhang ratio :

$$OR = \frac{A_{ova}}{A_{gf}}. \tag{2.12}$$

The MNLSI is the basic shear capacity of the critical story. The contributions of the columns, structural walls and unreinforced masonry walls are considered on this index. This index is the minimum value of A_{nx} and A_{ny} from Eq.2.13, which are total normalized lateral in the x and y directions, respectively. Also, A_{tf} corresponds to total story area above ground level:

$$\begin{aligned} A_{nx} &= \frac{\Sigma(A_{col})_x + \Sigma(A_{sw})_x + 0.1\Sigma(A_{mw})_x}{A_{tf}} \times 1000, \\ A_{ny} &= \frac{\Sigma(A_{col})_y + \Sigma(A_{sw})_y + 0.1\Sigma(A_{mw})_y}{A_{tf}} \times 1000. \end{aligned} \tag{2.13}$$

The lateral rigidity of the ground story, which is usually the most critical story, represents the lateral stiffness of the story and is taken into account through MNLSTFI, which is equal to the minimum of the indexes I_{nx} and I_{ny} computed for the in the x and y directions by using Eq.2.14, where $(I_{col})_x$ and $(I_{col})_y$ represent the moment of inertias of the columns, $(I_{sw})_x$ and

$(I_{sw})_y$ show the moment of inertias of the structural walls about the x and y axes, respectively.

$$I_{nx} = \frac{\Sigma(I_{col})_x + \Sigma(I_{sw})_x}{\Sigma A_{tf}} \times 1000,$$
$$I_{ny} = \frac{\Sigma(I_{col})_y + \Sigma(I_{sw})_y}{\Sigma A_{tf}} \times 1000. \quad (2.14)$$

The proposed variables by Yakut as mentioned beforehand were implemented and used in different studies [190, 73, 146, 209, 213].

2.5.2.2 Artificial Neural Networks (ANNs) and Machine Learning

ANNs are a kind of artificial intelligence application regarding the machine learning which has been applied by engineers for solving the challenges by using the general rules of human brain functions (e.g. memory, training). Consequently, using the ANNs make it likely to approximate the solution of difficulties like pattern recognition, organization, and estimation of functions by using the computers which use algorithms based on a dissimilar philosophy from traditional ones to overcome complicated difficulties affected by lots of factors [75]. Figure 2.9 shows a typical structure of ANNs, where it includes input layers, hidden layer, and output layer that in case of RVS can be different damage grades.

Though, using the ANNs for solving the civil engineering challenges began in 1989 by Adeli and Yen [4], who used them in the structural design process. Though, the early use of ANNs for damage estimation was encouraged to structures by strong ground signals offered by Molas and Yamazaki [123] in the mid-1990s. They studied ANNs' capability to estimate the seismic damage of wooden constructions quickly. Furthermore, they investigated the magnitude regarding the effect of seismic factors on the seismic damage by means of sensitivity examination.

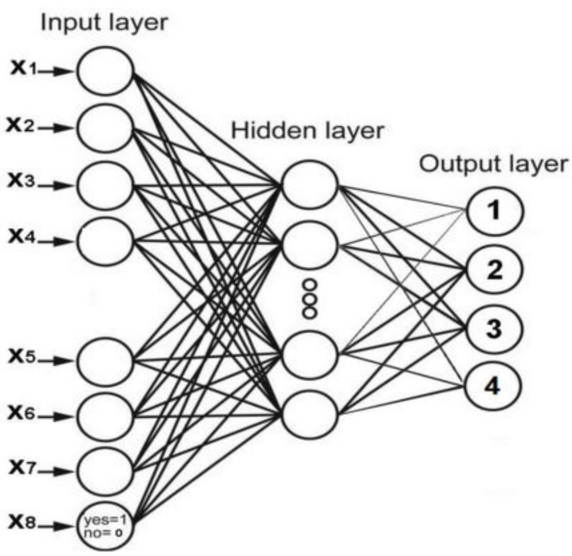


Figure 2.9: Typical structure of ANNs [69]

Caglar and Garip [30] trained a multi-layer perceptron (MLP) with a back-propagation (BP) algorithm by means of a database that was improved over a statistical process named P25 method. Their model was likewise examined over a verification set which establishes actual present RC constructions exposed to the 2003 Bingöl earthquake. The outcomes specified that the ANNs might forecast successfully the probable seismic performance level of current RC constructions, even if these constructions are not comprised in the dataset, that was used regarding the preparation.

Arslan [16] investigated the effect of structural parameters (like the amount of stories, the strength of concrete and steel, shear wall ratio, infill wall ratio) on the performance level of regular frame RC constructions under seismic excitation by means of ANNs. The data set regarding the preparation of the ANNs was created over the use of nonlinear pushover analyses. Later, Arslan et al. [17] applied data of 66 real four- to ten-story RC constructions, 19 structural input parameters, and numerous preparation algorithms, according to perceptron networks for estimating the earthquake performance level of present constructions [95]. But it should be noted that the selected ANN models in his investigation are valid merely for the exact ranges of the database. Consequently, the estimation capacity and duration of each algorithm is expected to be less than that considered in their investigation when the selected constructions are enlarged.

A study by Morfidis et al. [124] investigated the optimum combination of 14 seismic parameters for damage state prediction using ANNs. A set of 30 RC buildings complying with provisions of Euro Code 8 for elevation and plan dimensions were modeled elastically , analyzed, and designed using linear behavior. Furthermore, with lumped plasticity models, the nonlinear behavior were modeled by 65 horizontal bidirectional ground motions. For training the ANNs, Multi-layer Feedforward Perceptron networks were utilized. The Maximum Inter-story Drift Ratio (MIDR) obtained from the 3D nonlinear time history analysis of 30 buildings subjected to 65 actual ground motions were selected as the damage index to provide the data for the training data set. Their investigations for the methods adopted the Step-wise Method (Forward and Backward stepwise method) and the Weights method. They determined that a minimum of 5 seismic parameters should be used as inputs and substantiates the use of ANNs for damage prediction, but 11 to 14 parameters prove the best effective combinations [95].

Li and Wang [205] proposed a new technique for the seismic vulnerability of buildings using both neural network (NN) and convolution neural network (CNN). They have collected the building database of 6788 buildings from the 2011 New Zealand Christchurch earthquake (magnitude 6.3). Firstly, their CNN model was trained by 6000 buildings to utilize the spatially distributed information, PGV, soil liquefaction, and the distribution of neighboring houses. Later, it has been tested by the rest of the building's data (788), where they were classified into four damage states. The model trained with two hidden-layer NN with softmax activation function for output and achieved the mean accuracy of 86.5% after 1000 epochs [95].

Furthermore, a research presented by Tesfamariam and Liu [190] different classification techniques such as naive Bayes, k-nearest-neighbour (KNN), Fisher's linear discriminant analysis (FLDA), partial least squares discriminant analysis (PLSDA), multi-layer perceptron neural network (MLP-NN), classification tree (CT), support vector machine (SVM), and random forest (RF) applied on the database of 484 RC buildings that were damaged during Düzce earthquake 1999. They have used the common buildings variable proposed by Yakut et al. [209, 210]. For the training and testing their classification methods they have divided their database into ten sub-groups using the k-fold cross-validation method.

They have done the same procedure by considering 3 different steps of damage state. The first step consisted of all the five states of damage indicator (O, L, M, S, C), accompanying indicator as (1, 2, 3, 4, 5). Here the best classification method was SVM by having 45.7% accuracy, and the weakest was NB by showing 38.9% accuracy. The second step considered life safety (LS) performance classification. It had 0 for (O + L + M) damage states and 1 for

(S + C) damage states. Here the well-performed method was KNN by presenting 77.5%, and again NB was the least one by 74%. The third step acknowledged immediate occupancy (IO) performance classification. This step also sub-divided into two damage state, indicating 0 for (O + L) damage states and 1 for (M + S + C). In this condition, the SVM shows good accuracy by 72.3%, and the poor performance was 64% by RF.

Therefore, they have come to the conclusion that SVM is a proper tool for damage category classification; however, the selected data was limited and needs further improvement and calibration. In addition, they have investigated that N, SSI, and NRS were extremely critical parameters.

Harirchian et al. [69] studied the earthquake susceptibility through the combination of buildings' geometrical attributes that affect the vulnerability of buildings and can be used to obtain an optimal prediction of the damage state of RC buildings using ANNs. In this regard, an MLP network has been trained and optimized using a database of 145 damaged buildings from the Haiti earthquake. The results demonstrate the practicability and effectiveness of the selected ANNs approach to classify actual structural damage that can be used as a preliminary assessment procedure to recognize vulnerable buildings. Later, they have trained and tested their method on the building database of Düzce [73] and achieved significant improvements in comparison to the previous MLP methods on the same database. Their results show that an optimized MLP model with three hidden layers has high accuracy in detecting most vulnerable buildings (grade 5) but a low accuracy on severely damaged buildings (grade 4). Therefore, adding more variables (parameters that influence the structural behavior) to the input data leads to higher accuracy.

2.5.2.3 Summary

Different methods for vulnerability assessment of existing RC buildings based on statistical analysis, ML, and ANNs have been developed. But any ML is a computational process in which a prediction function is identified based on the input data. Therefore, a machine learning method is only as good as its input data. Each of these methods basically depends on the number considered parameters, limit to the specific area, and given data to classifies building damage grade. Therefore, there is a need to develop a robust method, which can be applied to different regions and conditions.

2.5.3 Methods Based on Rules and Expert Systems

An expert system is defined as an interactive and reliable computer-based decision-making system that uses both facts and heuristics to solve complex decision-making problems [82]. It is considered to be at the highest level of human intelligence and expertise. It is a computer application that solves the most complex issues in a specific domain. The expert system can resolve many issues which generally would require a human expert. It is based on knowledge acquired from an expert and is also capable of expressing and reasoning about some domain of knowledge [99].

Yadollahi et al. [206] illustrated the importance and usefulness of RVS and how to improve it for future assessment of buildings. Their proposed method uses functional vulnerability form for calculating the numeric scores for seismic vulnerability assessment of buildings. A case study had been carried out on ten buildings, in which each of the buildings is ranked based on the existing method FEMA 154. The previous approach, which based on a logarithmic relationship between the final score of the building to the probability of collapse, was complicated for non-experienced users to interpret, so an alternate non-logarithmic or linear format was proposed to ease the demand of decision-makers. The factors which played an essential part in seismic vulnerability score are (region seismicity, Structural Building type, vertical irregularity, plan irregularity, the height of the building, pre-code, post benchmark, soil type, and occupancy load). These factors are then compared with each other and grouped into five categories for hierarchy purpose using the Analytic Hierarchy Process (AHP) tool developed by Saaty [168]. About 10 pairwise comparisons have been made, and vulnerability score assignment for five factors took place, which includes region seismicity, structural building type, vertical and plan irregularity, pre-code/post benchmark. The region seismicity is divided into three categories low, moderate, and high. The proposed method by the author provides linear or non-logarithmic scores for better understanding by the decision-makers. All the factors concerning seismic vulnerability factors of the building are assessed, and correlative scores are assigned based on expert judgment. This method proved to be very useful in prioritizing the buildings, and the regional seismicity factor showed a significant concern in seismic vulnerability scores of buildings. The study revealed that 40% of the contribution to the seismic vulnerability score of buildings mostly depends on the location of the building.

There are as well different methods developed based on the application of multi-criteria decision making (MCDM) techniques and defining rules to assess earthquake hazard safety of buildings by rapid visual screening [66, 122]. But by developing technology and prove of fuzzy theory [214] to be an effective MCDM method [198], many researchers developed methods based on it. Fuzzy set theory is established and has been used in applications such as engineering, economic, environmental, social, medical, and management. Many of these types of problems take advantage of the availability of imprecise input. These types of applications favor a method that embraces vagueness and can be tested numerous times before real-world application.

Konstantinos and Stephanos [46] implemented a fuzzy logic–based rapid visual screening procedure for categorization of buildings into five different types of possible damage with respect to the potential occurrence of a major seismic event. They have studied on 102 buildings that were affected during Athens earthquake in 1999. The parameters they have used categorized as: 1-Seismic hazard (ground motion, soil quality, building height), 2-Structural strength (building height, infill wall layout, soft story, short columns, design code), 3-Regularity (plan regularity, torsion possibility, height regularity, pounding possibility, plan regularity), 4-Structure's condition (previous damage, maintenance). Their method was named as fuzzy logic-based Rapid Visual Screening Procedure (FL-RVSP) method and used for prioritizing buildings for further detailed investigations. Similar to many other methods it was classifying damage states into 5 groups, which were; operational, immediate occupancy, life safety, and collapse prevention, respectively [95].

Later, Moseley and Dritsos [125] by studying 101 and 454 buildings in Athens, Greece, utilized the fuzzy logic principle with rapid visual screening procedure to demonstrate buildings' seismic vulnerability, structural durability, and uniformity. Their focus behind this study was to assign a damage score for each building under observation, and the score could imply the degree of damage the building would endure in the course of a big earthquake. The built model used the data collected from the 102 damaged buildings during the Athens earthquake in 1999. For a better understanding, they assigned values 1, 2, and 3 to none, moderate and severe, respectively, to the buildings based upon their damaged condition. Their method was performing well to identify the most vulnerable buildings and about 60% to 80% of collapsed buildings. However, evaluation based on traditional RVSP had an efficiency of only 45% [95].

A study by Tesfamariam and Saatcioglu [191] on 93 RC (73 modeling and 20 test) buildings in Northridge, USA, proposed a risk-based seismic vulnerability assessment based on FEMA

154 and fuzzy logic for prioritizing buildings for retrofit and repair. The structural system, plan irregularity, vertical irregularity, year of construction, construction quality, building importance, and occupancy were the parameters they have considered. Furthermore, they have proposed another method [192] by using 28 RC buildings in Bingöl, Turkey.

According to their study, two factors affecting the building vulnerability including the factors that contributed to an increase in seismic demand, such as soft story, weak column-strong beam, vertical irregularities, and the second factor concentrated on the reduction of ductility and energy absorption capacity, such as construction quality, year of construction, structural degradation. Their work recommended for further calibration by using different data sets for better and optimized assessment.

A rule-based expert system developed by Gulkan and Yakut [63] for damage quantification in RC buildings. The main objective of this expert system is to tag buildings prone to failure in a subsequent aftershock, and hence to save lives. The rule-based expert systems integrate the severity of the member damage states, the extent of damage, and relative importance of the structural component to obtain member structural damage score. This procedure is applied to the whole building and using the if-then inference mechanism, the final damage state is determined.

Şen [171] developed a fuzzy logic model to evaluate 1249 existing RC buildings in the European side of Istanbul, Turkey. This pre-earthquake assessment considered different criteria such as story number, cantilever extension, soft story, weak story, building quality, pounding effect, hill-slope effect, and peak ground velocity. As seven parameters were considered, each with four sub classifications, the number of possible fuzzy sets is 12288, out of which only 1344 were logical ones. Later, proposed a fuzzy logic model as supervised hazard center classification inference methodology for rapid and rational hazard classification [172]. Building height, soft height ratio, cantilever extension ratio, the moment of inertia, frame number, column ratio, shear wall ratio, and PGV were the considered parameters. The tool was applied for the study of the Zeytinburnu quarter of Istanbul city, where around 16000 buildings were surveyed. Their evaluations figured out that only 747 buildings categorize as "slight" damage [95].

A study by Ketsap et al. [90] on the city Chiang Rai, Thailand proposed an earthquake risk evaluation of buildings by using the fuzzy risk model. For this evaluation, building occupancy (occupancy risk index), building vulnerability (FEMA 154 final score), Seismic hazard (PGA) were implemented into the Hierarchical fuzzy rule-based model.

2.5.3.1 Summary

There are different rule-based methods in which the most important one has been summarized, and for more detailed review can be referred to [70, 80]. Fuzzy set theory is an extension of classical set theory that "allows solving many problems related to dealing with the imprecise and uncertain data" [23]. But if the number of parameters is more, the fuzzy logics will increase, and selecting valid fuzzy logics is time-consuming. In rule-based methods, the availability of the system for the user is not an issue, and the output which has been generated by the system is dependent on rules, so the output responses are stable, which means it cannot be vague [169].

2.5.4 Heuristic and Other Methods

Miyasato et al. [121] have developed a simple hierarchical method for assessing seismic risk. The hierarchical structure is developed heuristically and calibrated for structures in California.

The uncertainty is captured by the safety factor.

The method presented by Hassan and Sozen [74] was a more accessible and less time-consuming vulnerability assessment method of ranking low-rise, RC and monolithic buildings in a region with infrequent earthquakes. A case study carried out on 46 Buildings after the 1992 Erzincan Earthquake in Turkey. Most of the buildings were low-rise institutional buildings with a maximum of five stories, had filler walls of stone, brick, or tile masonry. This method only requires the dimension of the structure as input and define the position on the two-dimensional plot. The proposed method was to rank all the buildings according to their Priority Index (PI) by considering the effective parameters which are: total floor area, RC wall area, masonry wall length, column index, wall index, that provide wall index (WI) and column index (CI) and will calculated as follow:

$$PI = CI + WI \tag{2.15}$$

Finally, the WI and CI values are plotted, which show a triangular damage state formulation at a specified threshold of WI and CI value. In evaluating a group of buildings, those with the lowest values of PI would be candidates for the earliest action. The main objective of this method was to reduce the time for vulnerability assessment in the region with infrequent earthquakes and to select the Buildings with higher seismic vulnerability. Gulkan and Sozen [62] have analytically showed the validity of the triangular formulation of Hassan and Sozen [74], albeit, with slight modification of the vertices of the triangle.

Yakut [208] has improved his previous method by incorporating indices related to building configuration, construction quality-related detailing, and lack of technical control. The procedure has been tested and calibrated based on the data compiled from damage surveys carried out after the earthquakes that took place within the previous years in Turkey. This approach is based on the calculation of the compressive strength of concrete and a capacity index by using the dimensions of the shear wall and column wall at the ground level. The total area of all the members is added by multiplying a factor. This factor depends upon the inclination of a longer dimension. These values help in the calculation of base shear capacity and are further adjusted by a factor that depends on the infill wall area. Accordingly, the shear capacity of infill walls is calculated when it is included in the building's base shear capacity. This shear capacity is further split up by the estimated shear demand of the building to acquire basic capacity index (BCPI).

The above method recommends that the shear demand can be calculated by using seismic codes. The value of BCPI is mainly used for normal or regular buildings which can be examined easily. In case of irregularities, a factor is multiplied which is lower then unity. The irregularities, as mentioned above, are the torsional irregularity due to overhangs and plan shape, short column and discontinuity of the structural members in plan, the vertical direction and soft story. Apart from that, a factor is multiplied to BCIP for consruction quality which divides it into three grades as per the quality of the building is concerned. These three grade are good, moderate, and bad, depending on the value of irregularity factor. A building is consider to be in good quality, if a value of unity is given to the building, for moderate and bad quality buildings it is given a score less then unity. Capacity index (CPI) is determined after the modification of the BCPI for irregularities in buildings and construction quality factors C_M take place . Increase in the capacity index of the building also increases the safety level of the building. The data which is required are the shear wall, compressive strength of the concrete, dimensions of the columns and infill walls at the ground story, soft story, construction quality, information about continuity of the members in plan and the vertical direction, number of stories, irregularity due to in plan non-uniformity and overhangs and soil class for determination of code shear demand.

This simple analytical technique can be used to discern the buildings which are vulnerable to seismic damage. The above four reported studies do not consider site seismic hazard and importance factor of the building, and thus do not explicitly consider risk.

Kanda et al. [86] have proposed a probability-based seismic safety evaluation of existing buildings through the second-moment seismic safety margin index β. The β is used to assess damage at different story levels. The ground motion model incorporates the duration of the motion, PGA, and in situ geotechnical condition. The proposed method was applied to eleven existing buildings in Japan. Later, Otani [141] demonstrated the seismic vulnerability assessment method for RC buildings in Japan. The proposed method is derived from building design equations, where the seismic capacity is obtained by considering capacity and demand. The method is expanded for a multi-degree freedom system and calibrated to account for discontinuity in stiffness along the building height and eccentricity in the plan.

Bal et al. [21, 22] proposed the "P25 Scoring Method" as a new approach for vulnerability assessment of RC buildings. Their method is very efficient to be used in densely populated areas like in old town. The main focus of this method is on the "collapse vulnerable" buildings. The method is applied to 323 RC buildings with different damage states, located in different soil conditions and subjected to various seismic actions.The method was based mainly on evaluating the critical parameters of a building, which significantly affect the seismic response. These parameters then scored with weighing factors and classified into seven different scores for the corresponding failure modes.

The first step of this method is to calculate P0 score,in order to calculate P0 score, building height,infill walls and shear walls at critical story and dimensions of columns is used. It rely on the total strength of the infill wall and RC members split-up by a factor for height of the building. Furthermore, P0 score is adjusted by the use of 14 separate "f factors" to obtain a P1 score. These 14 "f factors" include presence of mezzanine, soil type, foundation depth, corrections for torsional irregularity, concrete strength, slab discontinuity, discontinuity of elements in vertical direction, heavy cladding, mass irregularity, corrosion of reinforcement, different, lateral reinforcement spacing levels of story slabs and partial basement floor, weak-column strong-beam and foundation type.

After determining the basic structural score which is the P1 score, six additional scores are also calculated, which has a value from 0 to 100 depending on different deficiencies and irregularities. P2 score is for the existence of short column in a building and it depends upon the amount and length of short columns. P3 score determines the soft and weak story of a building and depends on the effective area of load carrying elements between different floors and differences of rigidity between them. P4 score is for the existence of overhangs in the building and continuity of frames. P5 score determines the pounding effect and it is given in the form of a table for separate cases ranging from 10 to 100. P6 score is for the effect of liquefaction and rely upon the liquefaction risk and depth of groundwater level. Lastly, P7 determines the soil failure score and it rely on the depth of groundwater level and soil type. The P scores for all the parameters are averaged with related significant factors, and the weighted mean score P_w, is computed. Regarding this P_w score, another factor known as β factor is also calculated. Furthermore, an α factor is also computed depending on the expected ground acceleration,topography of the site and significance of the observed building. Then the final value for the P score is determined according to the given Eq.2.16:

$$P = \alpha \times \beta \times P_{min} \tag{2.16}$$

The proposed method previously calibrated with 126 RC Buildings from different areas of Turkey and later applied to additional buildings, which totaled the numbers to 323. After calibration, 17 buildings experienced a collapse during the Earthquake. The past method used for Assessment is compared with the result of the P25 approach and showed a drastic change.

A scoring band developed from 0-100 varying the damage state from worst to best. Buildings that have a P score below 25 are considered as damaged or collapsed buildings. Buildings with P scores ranging between 26 to 34 are considered as moderate damage and they should be put forward for further investigation, and the building with P scores equal to 35 or more is regarded as a safe structure and it indicates safety against total collapse. Their investigations on case studies shows the high-risk Band is between 15 and 30, and the performance score of 30 considered as safety limit.

Al-Nimry et al. [10] generated a rapid assessment procedure that depends on building capacity index (i.e. base shear capacity of the building over the elastic base shear demand), seismicity level, local soil conditions, horizontal irregularities, soft story and overhangs, with different penalty scores assigned to the selected parameters. The multiplication of the penalty scores resulted in the capacity index, with buildings classified according to the capacity index.

2.6 Evaluation Requirements

To proceed with any aforementioned method, some primary information has to be obtained. A study by Stone [184] investigated the usefulness of building characteristics as inputs to seismic vulnerability assessment, as has been presented in the Figure 2.10.

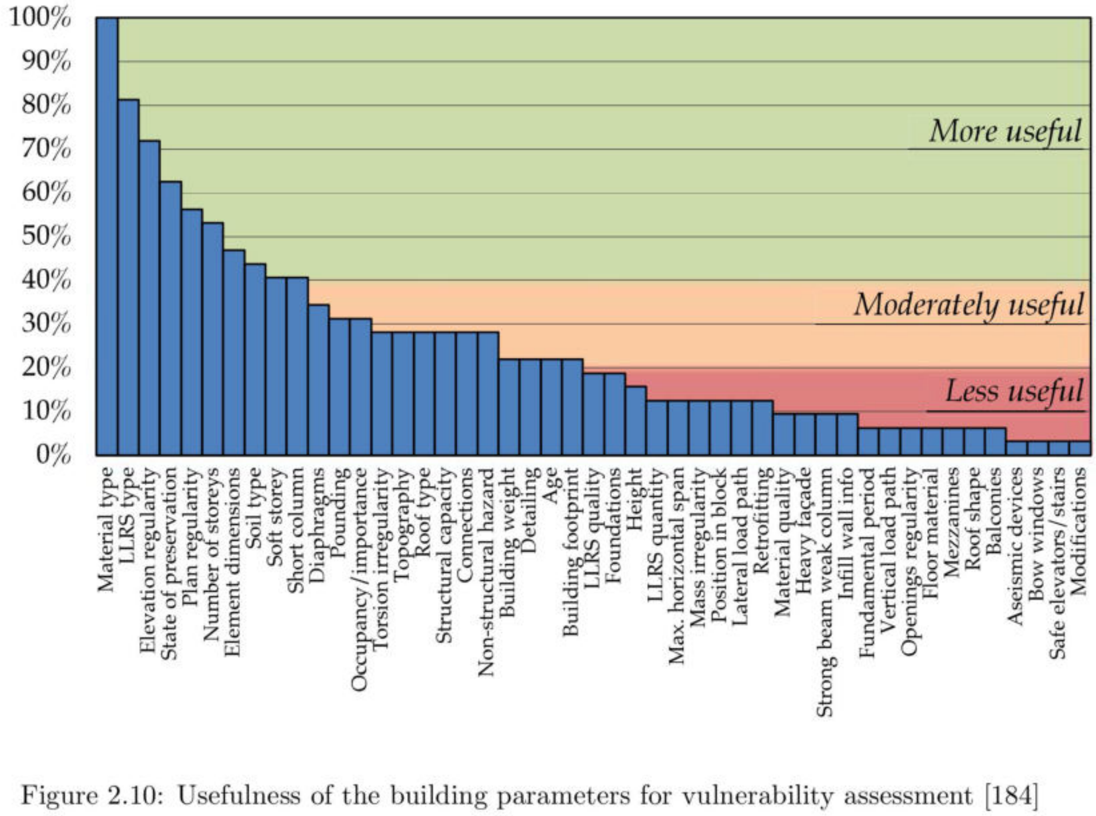


Figure 2.10: Usefulness of the building parameters for vulnerability assessment [184]

Therefore, in a street survey or site visit the required information and data will be collected, determine the general condition of the building, and assess the building conditions. Relevant building data that should be determined through a building observation includes:

- General building information: Number of stories, year of construction, dimensions, picture and address information, GPS coordination
- Building type: Identify and categorize the building as one or more of the common building types, as mentioned earlier, the focus in this thesis is on the RC buildings (C1, C2, and C3).
- Existence of irregularities: Any irregularity in plan and elevation of the building should be addressed.
- Region of seismicity: Identify the seismicity of the area which is under evaluation.
- Soil type: Note the soil type.
- Building occupancy and level of performance: The number of residents and the type of use of the building should be noted.

The building to be assessed must be classified as one or more of the building types based on the lateral-force-resistance systems. Two separate building types shall be used for buildings with different lateral-force-resisting systems in each of the two orthogonal directions. In this thesis, three concrete building types are considered; concrete moment frame (C1), concrete shear wall buildings (C2), and concrete frames with infill masonry (C3).

In this thesis, the terminology of earthquake hazard safety is used as seismic site condition is related to earthquake hazard and building vulnerability is related to safety; therefore, their integration has been considered.

This thesis defines and uses performance levels in accordance with FEMA 310 [3] and literature review. The process for defining the appropriate level of performance is the responsibility of the design professional or the authority having jurisdiction. Considerations in choosing an appropriate level of performance should include achieving basic safety, a cost-benefit analysis, the building occupancy type, and economic constraints [140]. Two performance levels for both structural and non-structural components are defined: Life Safety (LS) and Immediate Occupancy (IO). For both performance levels, the seismic demand is based on Maximum Considered Earthquake (MCE) spectral response acceleration values. Generally, buildings that are classified as essential facilities should be rated according to the (IO) performance level. The following buildings are required for post-disaster management and count as essential facilities [6]:

- Hospitals or other medical facilities having surgery or emergency treatment facilities,
- Fire or rescue and police stations,
- Power generating stations or other utilities required as emergency back-up, facilities for other facilities listed here,
- Emergency vehicle parking,
- Communication and internet centers,
- Buildings containing sufficient quantities of toxic or explosive substances deemed, to be dangerous to the public if released.

2.7 Discussion

In this chapter, different existing and proposed methods to evaluate earthquake hazard safety of buildings by RVS have been studied, classified, and discussed.

Generally, the methods of seismic screening are classified as predicted vulnerability or observed vulnerability procedures, or hybrid methods, depending on the type of source information used. Observed vulnerability procedures use statistics of damage in past earthquakes, sometimes combined with expert opinion, to determine the probable behavior of structures under future events. The main setback of this approach is the possible lack of observed data and the subjectivity in data interpretation. The observation-based approach also lacks analytical justification. Predicted vulnerability methods try to overcome these shortcomings by using analytical procedures to determine the probable behavior of a structure subjected to design-level earthquake loading. The limitation of this approach is the time and computational effort required by detailed analysis. Therefore, a balance between the effort, which needs to be relatively low per evaluated building and accuracy, which should be as high as possible, has to be found [52]. Another significant issue that has to be addressed by the new model is the improved accuracy and correlation between the damage score and rapid evaluation methods. A study by Ozmen [148] compared different RVS methods and noticed the maximum correlation factor of 0.28 is for the Ozcebe method. The correlation factors are 0.12 and 0.11 for the Yakut and P25 methods, respectively. Moreover a study by Harirchian et al. [71] expressed the low accuracy of the Turkish RVS and Indian RVS methods.

In addition to national and technical methods, there are methods proposed by the application of statistical analysis, machine learning techniques, and rule-based methods. Methods based on statistical approaches reduce the problem to a linear relationship between inputs and the output, which is not realistic as the relation between building parameters, seismicity parameters, and damageability is a non-linear relation. Methods based on machine learning and ANN approaches suffer from a lack of data where there are not enough databases consisting of building parameters before earthquakes and type of damage after earthquakes. In addition, these approaches are local and limited to a specific area; latter approaches, based on fuzzy systems, consider the expert's opinion, and model vagueness exists in words that describe the building parameters.

Fuzzy systems contributed significant achievements in vulnerability assessment due to making definite decisions based on imprecise or ambiguous data [60]. The main problem with all previous studies based on the conventional fuzzy logic system is that they only consider vagueness in membership functions while not including all types of uncertainties due to its crisp membership functions. However, this thesis proposes a method that will be described in the next sections to overcome the weakness of RVS methods.

Chapter 3

Research Methodology

3.1 Introduction

This chapter covers the proposed methodology for earthquake risk analysis of RC buildings. The previous chapter discussed different preliminary vulnerability assessment and RVS methods with their advantages and disadvantages in detail. It has been shown that there are three main categories: national methods, statistical and machine learning methods, and rule-based methods applied in the RVS procedure. The majority of those methods use performance modifiers to quantify building vulnerability congruence with FEMA 154, including: i) building type, ii) vertical irregularity, iii) plan irregularity, iv) year of construction, and v) construction quality. These performance modifiers can be collected easily through an observational survey and engineering drawings [195]. Additionally, there are some other effective factors, such as soil type and seismic hazards, which are available from seismic hazard maps and thorough site inspection. In addition, the importance of a building can be established with relative ease based on its use and occupancy. Determining these modifiers through an observational survey has subjective effects and uncertainties. These uncertainties can be modeled and handled through soft computing methods. The soft computing techniques include fuzzy-based approaches and investigate effectively the relationship between independent and dependent variables without any assumptions about the relationship (e.g., a linear relationship) between the various variables.

This chapter focused on fuzzy-based approaches and proposed a new RVS method and risk analysis of RC buildings using a hierarchical-based interval type-2 fuzzy system to address the uncertainty problem.

3.2 Soft Computing Techniques

The process of converting the input of one form to some other desired output form using certain control actions is called computation [120]. There are two types of computing: hard computing and soft computing. Hard computing is a process in which we program the computer to solve particular problems using mathematical algorithms that already exist, which provide a precise output value [91]. One of the fundamental examples of hard computing is a numerical problem. Soft computing is an approach where we compute solutions to the existing complex problems, where output results are imprecise or fuzzy in nature. One of the most important features of soft computing is that it should be adaptive so that any change in the environment does not affect strongly the present process [104].

In contrast to hard computing, soft computing treats approximate models and provides solutions to real life complex problems. As opposed to hard computing, soft computing tolerates inaccuracies, uncertainties, partial truths, and approximations [77]. In effect, the role model for soft computing is the human mind. Soft computing is based on techniques such as fuzzy logic, genetic algorithms, artificial neural networks, machine learning, and expert systems. Although the theory and techniques of soft computing were first introduced in the 1980s [216, 150], it has only now become an important area of research and investigation in engineering and technology [152]. The techniques of soft computing are being used successfully in many domestic, commercial, and industrial applications. With the advent of the low-cost and very high-performance digital processors and the reduction of the cost of memory chips, it is clear that the techniques and application areas of soft computing will continue to expand [94, 84].

One of the primary techniques of soft computing are fuzzy logic and expert systems, which are described briefly in the following parts. Fuzzy logic tries to model human judgment mathematically based on some rules and statements written by an expert. Human judgments may contain a verbal statement with vagueness or fuzziness. RVS is based on human observation of building; therefore, it is subjected to uncertainties and vagueness. The example of vagueness in the earthquake vulnerability assessment can be "The building is moderately vulnerable" or "The building is very important" or "The peak ground acceleration is high". Risk analysis problems contain a mixture of quantitative and qualitative data. Therefore, the analysis has widely adopted fuzzy logic, providing a language with semantics to translate qualitative knowledge into numerical reasoning. The substantial advantage of fuzzy logic is the ability to integrate descriptive or linguistic knowledge and numerical data to the fuzzy model and use approximate reasoning algorithms to propagate the uncertainties throughout the decision process [90].

3.2.1 Type-1 Fuzzy Logic System (T1FLS)

Fuzzy logic has been introduced by Zadeh in the 1960s [214]. The term "Fuzzy" is used as an extension for traditional binary set of True or False to deal with concepts of logics like "Partially True". Since then, it has been applied to many areas, including control systems [98], time-series prediction [92], and seismic vulnerability assessments [101]. Fuzzy modeling is the most common application area of fuzzy logic [207]. Two main fuzzy models are Mamdani [93] and Takagi-Sugeno [187]. The fuzzy model introduced by Mamdani is the most widely used model. All the results reported in this study consider this model.

A fuzzy model can be determined by [25]:

1. Using available measurements and identification methods, e.g., clustering methods to find the parameters and fuzzy terms of the rules describing the system,

2. Using *a priori* knowledge about the system provided as rules by system designers and experts.

In seismic vulnerability assessment, there is a lack and limitation of available measurement. Therefore, modeling RVS based on the former fuzzy model (1) has some inaccuracies. However, applying the latter fuzzy model (2) which uses expert's knowledge has more advantages in RVS procedures. Moreover, to improve the accuracy of the model, the fuzzy rules and parameters can be modified based on previous earthquake results, if available.

A crisp set has a binary membership function of 0 or 1. A type-1 fuzzy set is a generalized version of a crisp set where the membership function is defined on interval of [0,1]. Let A be a fuzzy set on a universe of discourse U with a membership grade of $\mu_A(x)$ that takes on values in the interval [0,1]. When U is continuous, A can be defined as [49]:

$$A = \int_U \frac{\mu_A(x)}{x} \tag{3.1}$$

Here $\int$ does not denote integration; it denotes the collection of all points $x \in U$ with related membership grade $\mu_A(x)$.

There are different types of membership functions which can be used to graphically represent a fuzzy set. These membership functions can be as simple as a rectangular function or as complicated as a Gaussian function. Figure 3.1 shows typical types of these membership functions. The x axis represents the universe of discourse, whereas the y axis represents the degrees of membership in the [0,1] interval. Here, triangular functions, as can be seen in Figure 3.1, are defined by *a* lower limit *b*, an upper limit *c*, and *a* value *m*, where b<m<c and membership values are represented by Eq.3.2.

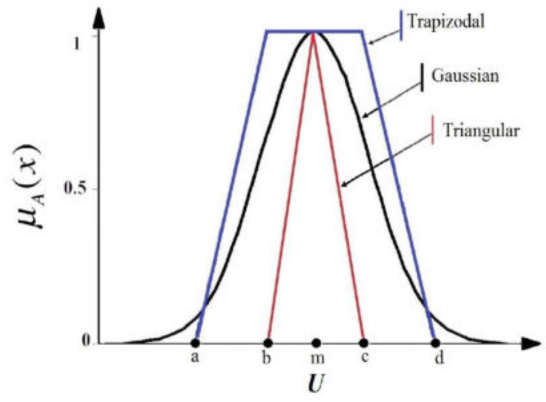


Figure 3.1: Typical fuzzy type-1 membership functions

$$\mu_A(x) = \begin{cases} 0 & x \leq b \\ \frac{x-b}{m-b} & b < x \leq m \\ \frac{c-x}{c-m} & m < x < c \\ 0 & x \geq c \end{cases} \tag{3.2}$$

Trapezoidal functions are defined by a lower limit *a*, an upper limit *d*, a lower support limit *b*, and an upper support limit *c*, where $a<b<c<d$ and expressed in Eq.3.3.

$$\mu_A(x) = \begin{cases} 0 & (x < a) \ or \ (x > d) \\ \frac{x-a}{b-a} & a \leq x \leq b \\ 1 & b \leq x \leq c \\ \frac{d-x}{d-c} & c \leq x \leq d \end{cases} \tag{3.3}$$

Gaussian functions are determined by a central value m and a standard deviation $k > 0$. The smaller k is, the narrower the "bell" is. The Gaussian membership value is represented by Eq.3.4.

$$\mu_A(x) = e^{-\frac{(x-m)^2}{2k^2}} \tag{3.4}$$

Fuzzy logic includes fuzzy linguistic variables, which are words or sentences in a natural or artificial language used to represent the qualities of an input. For example, speed is a linguistic variable that can take the values as slow, medium, fast. A fuzzy system also has fuzzy operators, e.g., fuzzy *And* and fuzzy *OR*. These operators are used on antecedent and consequent of rules in order to apply implication methods.

A T1FLS contains four components: Fuzzification, Rule Base, Inference Engine, and Defuzzification, as illustrated in Figure 3.2 and described below.

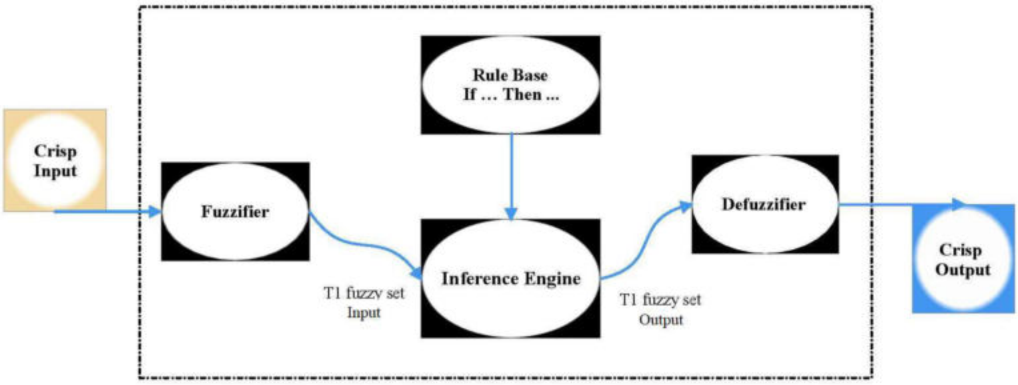


Figure 3.2: Components of a T1FLS [107]

Fuzzification: the process of changing a crisp value into a fuzzy value. This is achieved with the different types of Fuzzifier, which are a combination of fuzzy sets or membership functions for each input.
Inference Engine: fuzzy inference is a method that interprets the values in the input vector and, based on some sets of rules, assigns values to the output vector.
Defuzzification: the process of producing a crisp value, given fuzzy sets and corresponding membership functions. This is achieved with the different types of Defuzzifier, like centroid or mean of output fuzzy set.
Rule Base: a collection of IF-THEN statements representing a mapping of the system from a set of fuzzy inputs to a set of fuzzy outputs in the following form:

$$R^l : \text{IF} \quad x_1 \text{ is } X_1^l \text{ and } \quad \text{IF} \quad x_2 \quad \text{is } X_2^l \quad \text{and ... and} \quad \text{IF} \quad x_n \text{ is } X_n^l \quad \text{THEN} \quad y\ is\ Y^l \tag{3.5}$$

Where l is the rule index, X_i^l $(i = 1, 2, ..., n)$, Y^l are type-1 fuzzy sets on U_i and V, respectively, $x = (x_1, x_2, ..., x_n) \in U_1 \times U_2 \times ... \times U_n \equiv U$ and $y \in V$ are linguistic variables. Here x and y are input and output of fuzzy model, respectively.

IF-part of a rule is called "antecedent", where THEN-part of the rule is called "consequent". A consequent is a fuzzy set represented by a membership function, which weights appropriately the linguistic characteristics that are attributed to it. The consequent is reshaped using a function associated with the antecedent (a single number).
The process of a FLS system is as follows:

First, all rules are defined, and crisp input values are converted to fuzzy values via the fuzzification process. After defining all rules and fuzzifying input variables, the implication method is implemented for each rule. The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. After implication applied to all rules, the next step is aggregation. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. In other words, the input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable. Finally, the resulting fuzzy set is converted to a crisp value using defuzzification methods, e.g., centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum.

There are (at least) four sources of uncertainties in T1FLSs [113, 204]:

1. Uncertain words: the meanings of the words that are used in the antecedents and consequents of rules can be uncertain (words mean different things to different people).
2. Uncertain consequents: consequents may have a histogram of values associated with them, mainly when knowledge is extracted from a group of experts who do not all agree.
3. Noisy measurements: measurements that activate a T1FLS may be noisy and, therefore, uncertain.
4. Membership function parameters: the data used to tune the parameters of a T1FLS may also be noisy and therefore uncertain.

All of these uncertainties translate into uncertainties about fuzzy set membership functions. Type-1 fuzzy sets are not able to directly model such uncertainties because their membership functions are crisp. On the other hand, type-2 fuzzy sets are able to model such uncertainties because their membership functions are themselves fuzzy. Membership functions of type-1 fuzzy sets are two-dimensional, whereas membership functions of type-2 fuzzy sets are three-dimensional. It is the new third-dimension of type-2 fuzzy sets that provides additional degrees of freedom, making it possible to directly model uncertainties.

3.2.2 Type-2 Fuzzy Logic System (T2FLS)

Lotfi Zadeh introduced the initial concept of fuzzy set (type-1) in 1965 [214] and later in 1975 developed the extension of it as the type-2 fuzzy set [215]. The main limitation of the T1FLS is that it cannot adequately handle the linguistic, measurement, and parameter uncertainties [188] due to the beforehand mentioned problems [113]. In this regard, T2FLS, characterized by MFs that are themselves fuzzy, therefore, in case there are difficulties in the determination of membership grade even as a crisp number in [0,1], type-2 fuzzy sets are then adequate to use. So far, T2FLSs have been used in different areas to deal with high uncertainty, non-linearity and time-varying behavior [34], including computing with words [111], intelligent controllers [65], pattern recognition [117], and so on. A general T2FLS requires extensive computational power and complicated implementation compared to a T1FLS [132]. Therefore, a special case of T2FLS, interval type-2 FLS (IT2FLS) has been widely used for reduced computational burden [114, 116].

A IT2FLS, as has been presented in Figure 3.3 consists of five parts as fuzzifier, rule base, inference engine, type-reducer, and defuzzifier. In IT2FLS, at least one of the fuzzy sets (membership functions) in the rule base must be type-2. All parts of IT2FLS are similar to T1FLS except the type-reducer, which is introduced to convert the type-2 membership functions into a type-1 before defuzzification. The process of type-reduction is usually performed by the most popular computationally intensive Karnik-Mendel (KM) iterative algorithms proposed by Wu and Mendel [203].

A type-2 fuzzy set $\tilde{A}$ can be defined by its type-2 membership function $\mu_{\tilde{A}}(x,u)$ as:

$$\tilde{A} = \int_{x \in X} \int_{u \in J_x} \frac{\mu_{\tilde{A}}(x,u)}{(x,u)}, \tag{3.6}$$

where $x \in X$, $u \in J_x \subseteq [0\ ,1]$, and X represent the universe of the primary variable x of $\tilde{A}$. Here $\int\int$ denotes all the admissible x and u. The point-value representation of $\tilde{A}$ is as:

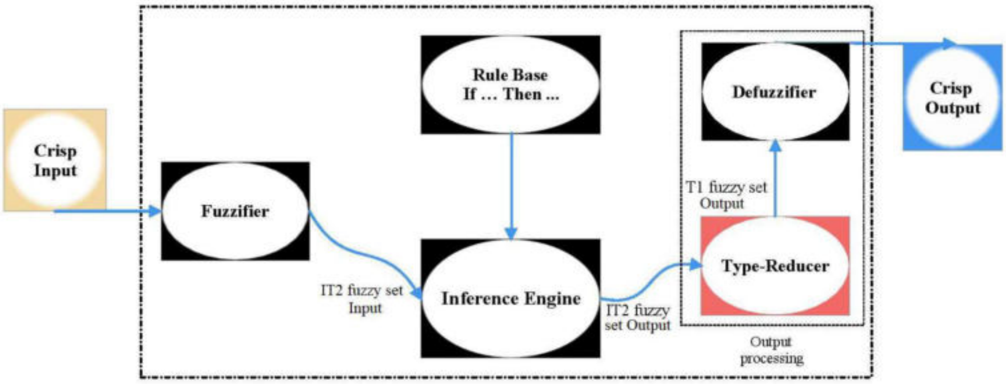


Figure 3.3: Components of an IT2FLS [107]

$$\tilde{A} = \Big\{((x,u), \mu_{\tilde{A}}(x,u)) \mid \forall x \in X, \forall u \in [0,1]\Big\}. \tag{3.7}$$

The secondary MF of Ã is also called a vertical slice of $\mu_{\tilde{A}}(x,u)$:

$$\mu_{\tilde{A}}(x = x', u) \equiv \mu_{\tilde{A}}(x', u) = \int_{u \in J_{x'}} \frac{f_{x'}(u)}{u}, \tag{3.8}$$

where $0 \leq f_{x'}(u) \leq 1$, and $\mu_{\tilde{A}}(x', u)$ denotes the secondary MF of Ã. The secondary membership grades of IT2FS all equal 1, that is to say, for any x=x', $f_{x'}(u) \equiv 1$.

The third dimension value in the IT2FS is the same everywhere so that it is ignored and only the footprint of uncertainty is used to describe the IT2FS. Figure 3.4 illustrates a Gaussian type-1 fuzzy set and its correlation to a Gaussian interval type-2 fuzzy set.

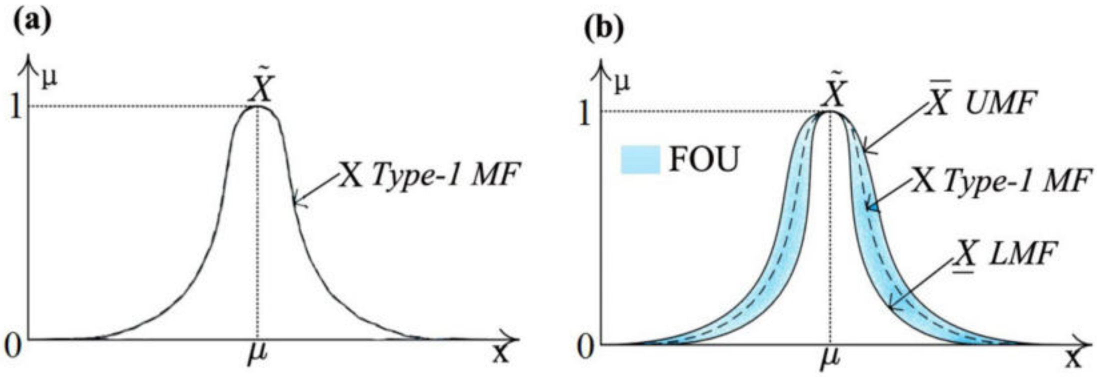


Figure 3.4: (a) A Gaussian T1 fuzzy set, (b) A Gaussian IT2 fuzzy set

Type-2 carries the footprint of uncertainty (FOU), upper membership functions (UMFs) and lower membership function (LMFs). The FOU is uncertainty in the primary membership grades of a type-2 MF, which consists of a bounded region; the UMF is a subset that has the maximum membership grade of the FOU, and the LMF is a subset that has the minimum membership grade of the FOU. The two-dimensional $\mu_{\tilde{A}}(x,u)$ is referred to as the footprint of uncertainty (FOU) of Ã:

$$FOU(\tilde{A}) = \bigcup_{x \in X} J_x = \{(x,u) | u \in J_x \subseteq [0,1]\}, \tag{3.9}$$

where J_x is the primary membership of Ã; here the lower MF (LMF) $\underline{\mu}_{\tilde{A}}(x)$ and upper MF (UMF) $\overline{\mu}_{\tilde{A}}(x)$ comprise the FOU, where [7]:

$$\underline{\mu}_{\tilde{A}}(x) = LMF(\tilde{A}) = \inf\{u | u \in [0,1], \mu_{\tilde{A}}(x,u) > 0\}, \tag{3.10}$$

and

$$\overline{\mu}_{\tilde{A}}(x) = UMF(\tilde{A}) = \sup\{u | u \in [0,1], \mu_{\tilde{A}}(x,u) > 0\}. \tag{3.11}$$

There are two types of T2FLSs : Mamdani and Takagi-sugeno [34]. Here, our focus is on Mamdani type as it is more easier than Takagi-Sugeno and also the consequence of it is fuzzy. Therefore, the rules of IF-THEN [35] can be written as:

$$\tilde{R}^l : \text{IF} \quad x_1 \; is \; \tilde{F}_1^l \quad \text{and ...} \quad x_p \; is \; \tilde{F}_p^l \quad \text{THEN} \quad y \; is \; \tilde{G}^l \quad l = 1, ..., N, \tag{3.12}$$

or in another way:

$$\tilde{R}^l : \tilde{F}_1^l \times ... \times \tilde{F}_p^l \rightarrow \tilde{G}^l = \tilde{A}^l \rightarrow \tilde{G}^l, \tag{3.13}$$

where l is the rule number, x_i and $\tilde{F}_i^l$ are the ith (i=1,...,p) input and antecedent set of rule l, respectively, G^l are consequent sets and A is the input fuzzy sets, while y is the output and "∼" shows that the fuzzy set is a T2 fuzzy set.

According to equation 3.13, the output of the inference engine for each rule can be defined as [34]:

$$\mu_{\tilde{B}^l}(y) = \mu_{\tilde{A}^l \rightarrow \tilde{G}^l}(x,y) = \mu_{\tilde{F}_1^l(x_1')} \cap ... \cap \mu_{\tilde{F}_p^l}(x_p') \cap \mu_{\tilde{G}}(y) = \left[\bigcap_{i=1}^{p} \mu_{\tilde{F}_i^l}(x_i') \right] \cap \mu_{\tilde{G}}(y). \tag{3.14}$$

Figure 3.5 shows an example of firing interval of two triangle T2 fuzzy sets for a rule (l_1) in which minimization (∩) is used for.

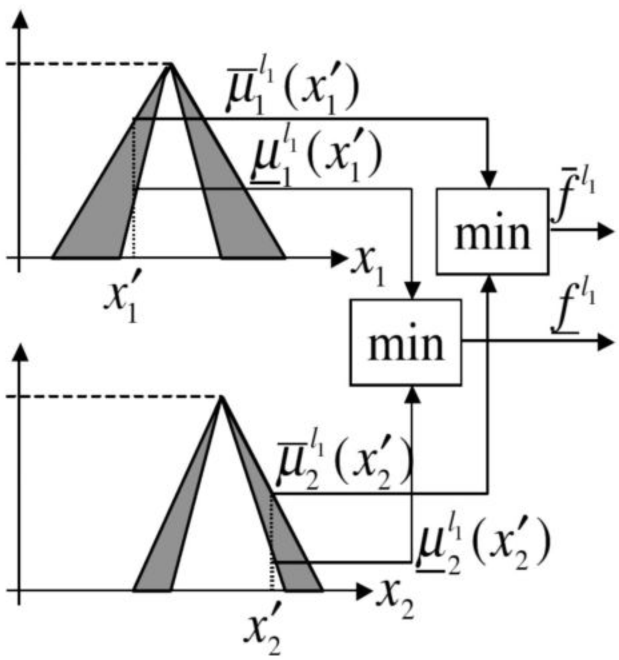


Figure 3.5: Example of firing interval of two triangle T2 fuzzy sets for a rule (l_1) (from [109])

While adopting the popular centroid type-reduction [102], the firing output set $\tilde{B}^l$ is generated by each fuzzy rule and the corresponding consequent IT2FLS:

$$\tilde{B}^l : \begin{cases} FOU(\tilde{B}^l) = [\underline{\mu}_{\tilde{B}^l}(y \mid x'), \overline{\mu}_{\tilde{B}^l}(y \mid x')] \\ \underline{\mu}_{\tilde{B}^l}(y \mid x') = \underline{f}^l(x') \cap \underline{\mu}_{\tilde{G}^l}(y) \\ \overline{\mu}_{\tilde{B}^l}(y \mid x') = \overline{f}^l(x') \cap \underline{\mu}_{\tilde{G}^l}(y), \end{cases} \tag{3.15}$$

where $\cap$ denotes the minimum or product t-norm operation. Figure 3.6 shows an example of outputs of two different rules (l_1, l_2), where the gray triangle is the consequent side ($\mu_{\tilde{G}}(y)$) and the highlighted red parts show the implication (minimization) of the antecedent and consequent, here $b^l(y)$, is the firing output set.

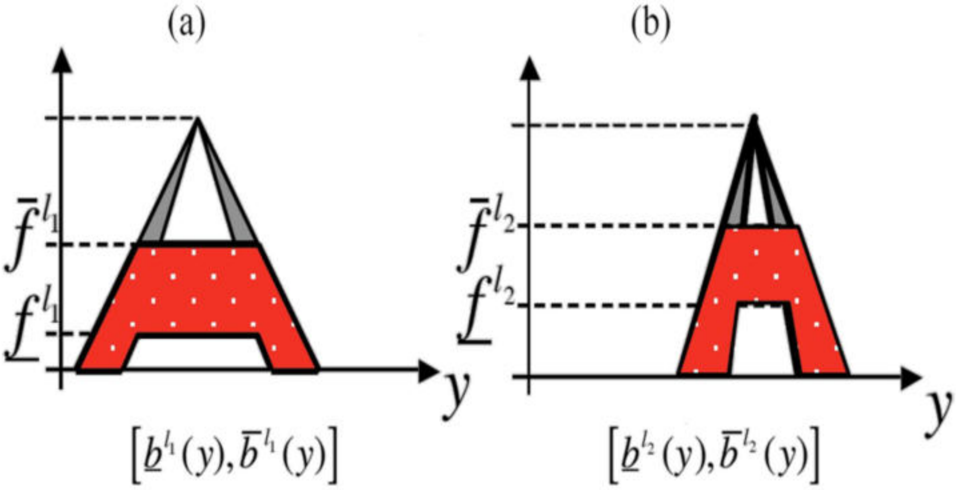


Figure 3.6: (a) Rule (l_1) output, (b) Rule (l_2) output (adopted from [109])

The final output $\tilde{B}$ can be achieved by merging all the rule firing output sets $\tilde{B}^l$:

$$\tilde{B} : \begin{cases} FOU(\tilde{B}) = [\underline{\mu}_{\tilde{B}}(y \mid x'), \overline{\mu}_{\tilde{B}}(y \mid x')] \\ \underline{\mu}_{\tilde{B}}(y \mid x') = \underline{\mu}_{\tilde{B}^l}(y \mid x') \cup ... \cup \underline{\mu}_{\tilde{B}^M}(y \mid x') \\ \overline{\mu}_{\tilde{B}}(y \mid x') = \overline{\mu}_{\tilde{B}^l}(y \mid x') \cup ... \cup \overline{\mu}_{\tilde{B}^M}(y \mid x'). \end{cases} \tag{3.16}$$

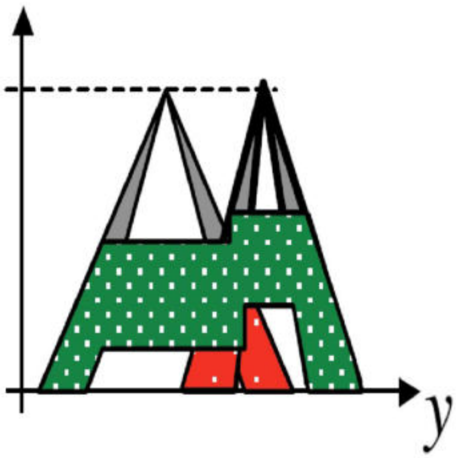


Figure 3.7: Combined output - a T2FS (adopted from [109])

Figure 3.7 presents the aggregation of the rules output. In the Eq.3.16, $\cup$ indicates the maximum operation. Then the type-reduced set $Y_c(x')$ can be obtained by computing the centroid $C_{\tilde{B}}$ of $\tilde{B}$:

$$Y_c(x') = C_{\tilde{B}}(x') = \frac{1}{[l_{\tilde{B}}(x'), r_{\tilde{B}}(x')]}. \tag{3.17}$$

The two points (switch points) $l_{\tilde{B}}(x')$ and $r_{\tilde{B}}(x')$ as lower limit and upper limit of $\tilde{B}$, respectively, are estimated by various type-reduction algorithms such as Karnik-Mendel (KM) [110], Enhanced Karnik-Mendel (EKM) [202], and weighted EKM [103].

3.3 Development of a Hierarchical Structure for Earthquake Risk Analysis

The earthquake risk analysis generally comprises the followings steps, seismic hazard assessment of the site, data collection, vulnerability assessment of building as well as the discipline of economic and social sciences unravel [180]. Crowley [42] described the earthquake risk at a given site is the probability of loss and acquire through the complexity of exposure, seismic hazard and vulnerability. The total number of human activity in that specific zone which is prone to seismic hazard specified by the stock of building in that specific location is called exposure; probability of a certain ground motion occurring at a location is called hazard and vulnerability is defined as the susceptibility of the building [43]. The complex problem of earthquake risk analysis can be grouped into a simple and manageable hierarchical structure. It will also help to minimize the rules of the fuzzy logic system, increase the speed of calculation, and simplify the problem.

Figure 3.8 shows a schematic of the proposed general framework to quantify earthquake risk of RC buildings. As it can be seen, the first three principal components are labeled as *Main Phase* and include: i) seismic site condition, ii) building vulnerability, and iii) building importance/exposure.

After collecting the required inputs of performance modifiers of the *Main Phase*, the relevant indices are calculated through the process of fuzzification, and aggregation as part of the *Assessment Phase*. Finally, during the *index phase*, the earthquake hazard safety index of building and building importance/exposure index result in the earthquake risk index.

The expansions of the hierarchical model as one of the novelties of this thesis are presented as a Fishbone diagram (Ishikawa diagram) in Figure 3.9. The hierarchical Fishbone diagram has a logical order where the causal relationship for each supporting argument is further subdivided into specific contributors. In this figure, the outcome of each fuzzy system is showing as R.

The process of quantifying the proposed earthquake risk index involves the steps illustrated in Figure 3.10. As can be seen, the process starts with the collection of relevant performance modifiers by a walk-down survey of buildings. After the collection of required inputs, they will be transformed into commensurable units through fuzzification. Later, aggregate the hazard performance modifiers to obtain the seismic site condition index, which will be described in detail further. After this, the earthquake hazard safety index will be computed from the collected information. Afterwards, by aggregation of importance/exposure performance modifiers, the importance/exposure index will be obtained. Consequently, by having all the indices, the earthquake risk index of buildings can be calculated. As the proposed method has this ability to give the earthquake risk index based on the time of the event, the time of the event can aggregate with the inputs of importance/exposure to obtain on-time risk level of buildings for rescue and emergency purposes.

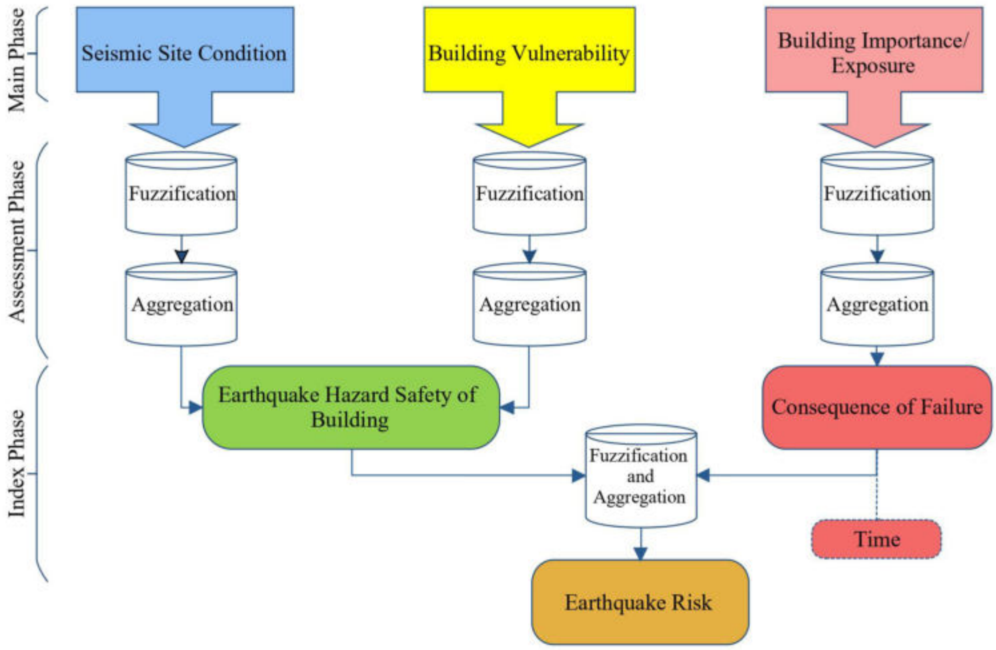


Figure 3.8: Earthquake risk analysis of RC buildings

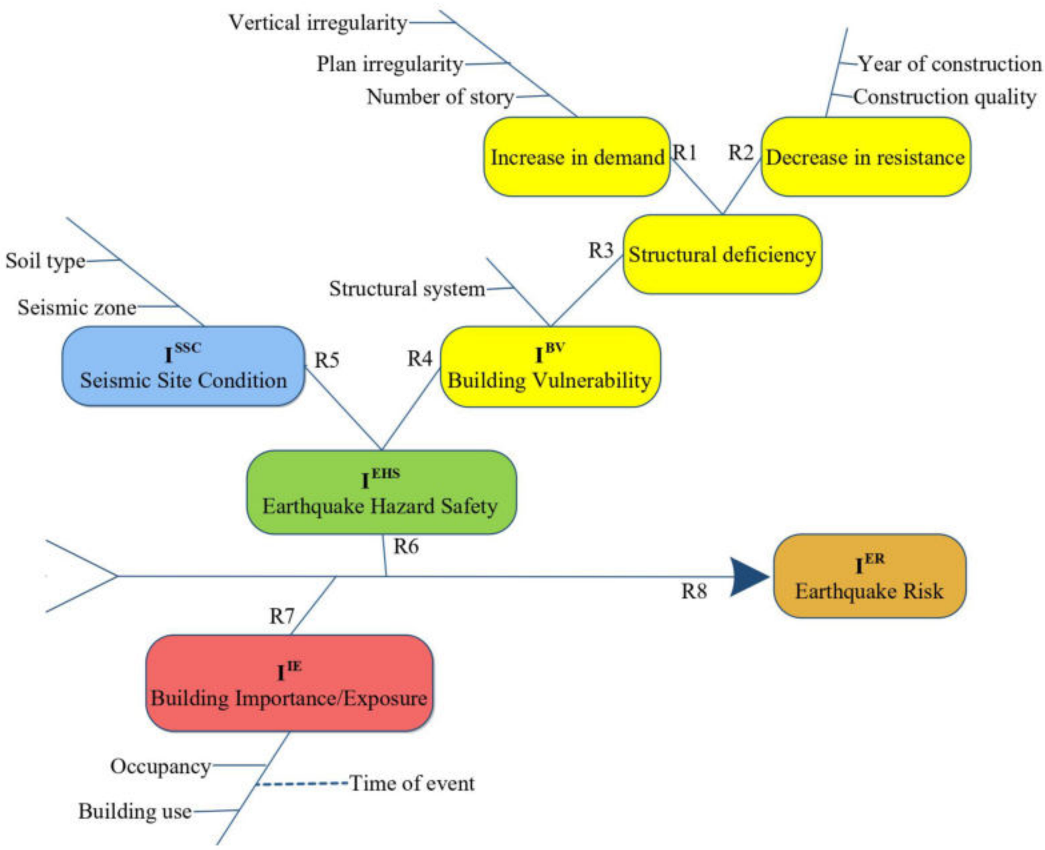


Figure 3.9: Fishbone diagram of earthquake risk analysis of RC buildings

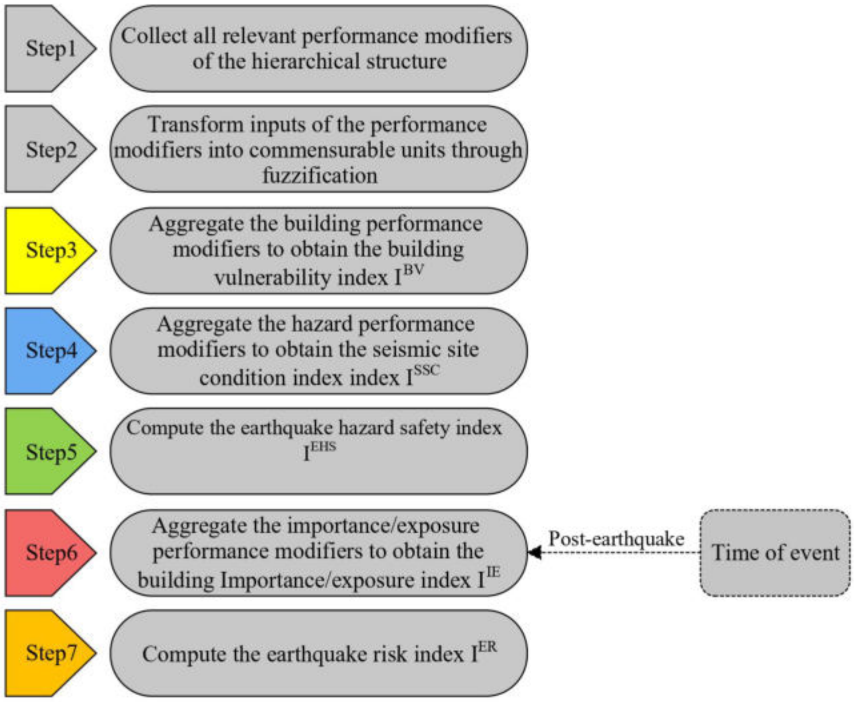


Figure 3.10: Steps of quantifying the earthquake risk index

This study deals with the vulnerability assessment of RC structures by defining an earthquake hazard safety index. Therefore, the proposed methodology uses the parameters described in the RVS developed in the FEMA P-154 handbook [195] and modifies them into a fuzzy inference system and defined rules based on literature to estimate the vulnerability and safety of buildings for pre-earthquake and to prioritize buildings for post-earthquake rescue services. Nonetheless, other parameters based on their application and effectiveness have been used according to the literature review.

3.3.1 Seismic Site Condition Index I^{SSC}

The outcome of seismic site condition phase by considering practical parameters is the seismic site condition index I^{SSC} and is evaluated as *High*, *Medium*, and *Low*. The practical parameters are seismic zone and soil type of the selected building.

3.3.1.1 Seismic Zone

The FEMA P-154 supplied data forms for various degrees of seismicity. Depending on the seismicity classification, the relevant data form must be chosen. The classification of levels of seismicity is based on the spectral response acceleration values, as shown in Table 3.1 according to U.S. Geological Survey (USGS) [57, 195], where S_s is the spectral response acceleration parameter for 5%-damped maximum considered earthquake (MCE_R) of a period of 0.2 seconds (short period), and S_1, the spectral response acceleration parameter for 5%-damped MCE_R for a period of 1 second (long period), assuming Soil Type B and g is acceleration of gravity in the horizontal direction. This table can be used to select the appropriate seismicity region, assuming that the highest seismicity level defined by the parameters in Table 3.1 shall govern. In this thesis the seismic zone considered as Low *(L)*, Moderate *(M)*, Moderately high *(MH)*, High *(H)*, and Very high *(VH)*.

Table 3.1: Range and Median MCE_R spectral response acceleration values in each seismic region [55]

Seismicity Region	Range of Response Values for Each Region	
	$S_s(g)$	$S_1(g)$
Low(L)	$S_s < 0.25g$	$S_1 < 0.1g$
Moderate (M)	$0.25g \leq S_s < 0.5g$	$0.1g \leq S_1 < 0.2g$
Moderately High (MH)	$0.5g \leq S_s < 1g$	$0.2g \leq S_1 < 0.4g$
High (H)	$1g \leq S_s < 1.5g$	$0.4g \leq S_1 < 0.6g$
Very High (VH)	$S_s \geq 1.5g$	$S_1 \geq 0.6g$

To calculate input values of fuzzy system based on Table 3.1, we combine S_s and S_1 as one equation to calculate the range for fuzzy sets. Therefore, the input values can be calculated as: S_{value}=$(S_s + S_1)/2$ Therefore the interval for each seismic region is as follows:

- S_{value} *(L)* <(0.25+0.1)/2 = 0.175,
- S_{value} *(M)* : (0.25+0.1)/2=0.175 ≤ S_{value} <(0.5+0.2)/2 = 0.35,
- S_{value} *(MH)* : (0.5+0.2)/2 = 0.35 ≤ S_{value} <(1+0.4)/2 = 0.7,
- S_{value} *(H and VH)* ≥ 0.7.

3.3.1.2 Soil Type

National Earthquake Hazard Reduction Program (NEHRP) [39] in code provisions has divided soil/ground into different classes of average shear wave velocity of the ground in the uppermost 30 m (V_{s30}) as presented in Table 3.2. In this thesis, the soil type considered as Rock *(A or B)*, Dense soil *(C)*, Stiff soil *(D)*, and Soft *(E)*. The soil type F is a special soil type due to its liquidation and requires special evaluation and is outside the scope of this thesis. V_{s30} values can be obtained by using the Global V_{s30} Map Server developed by Wald and Allen [199] or any other resources.

Table 3.2: Soil site classification according to NEHRP [39]

Soil Type	Description	Average V_{s30} (m/s)
A	Hard rock	V_{s30}>1500
B	Rock	760 <V_{s30}<1500
C	Dense soil/soft rock	360 <V_{s30}<760
D	Stiff soil	180<V_{s30}<360
E	Soft soil	V_{s30}<180
F	Special soil	require special evaluation

To calculate input values of fuzzy system based on Table 3.2, as mentioned previously, 4 soil types including A *or* B, C, D, and E have been considered and will be calculated as follows:

- S_{value} *(E)* < 180/100=0.18,
- S_{value} *(D)* : 0.18 < S_{value} < 360/100=0.36,
- S_{value} *(C)* : 0.36 < S_{value} < 760/100=0.76,
- S_{value} *(A or B)* > 0.76.

3.3.2 Building Vulnerability Index I^{BV}

Integrating the inherent implicit inadequacies within the structure are the basis for computing the building vulnerability (shown in Figure 3.9). This phase largely depends on the significance of: i) structural system configuration, e.g., shear wall or moment-resisting frame buildings, and ii) structural inadequacy or deficiency, e.g., plan irregularity. The structural deficiencies are further branched into performance modifiers that significantly contribute to an elevation in seismic demand and decline in structural capacity to seismic hazard resistance. Vertical irregularity, plan irregularity, and number of stories are specifically the parameters which contribute to an increase in seismic demand. On the contrary, construction quality and the year of construction contribute substantially towards the decrease in seismic resistance. The outcome of building vulnerability phase by considering practical parameters is the building vulnerability index I^{BV}.

3.3.2.1 Structural System

A study by Arslan [16] found that shear wall ratio and short column formation are the most significant structural components that affect performance. The compressive strength of concrete and transverse reinforcement were determined to be the least significant parameters. Therefore, the extent of building damage is related to the features of the structural system, which include many parameters. In particular, it is difficult to determine the extent to which structural parameters affect structural performance to identify the main parameters that may cause damage to buildings [16]. However, the configuration of lateral force resisting system in a building plays a consequential role in terms of resistance to seismic loads.

The scope of this thesis includes RC buildings; therefore, the three types of RC buildings considered are moment resisting frames (C1), shear wall buildings (C2), and moment-resisting frames with infill masonry walls (C3). Shear walls with attributes of sufficient rigidity when used in structures are proven to resist the seismic forces in a highly efficient manner. Although it is known that the engineering domain uses the term "shear wall" very extensively, their paramount mode of behavior can be flexible with respect to medium or high-rise structures. They substantially act as vertical cantilevers thereby assigning lateral bracing to the whole system, whereas on the other hand, receiving lateral forces from diaphragms and channeling them to the structural foundation. Seismic resistance is critically by virtue of size and location. Before the compliance of new seismic codes the shear walls were lightly reinforced flexible elements which usually extending throughout the structural height of building. In modern constructions, shear walls occur in more isolated locations and are significantly heavy reinforced. Shear wall structures are substantially manifested to behave efficiently under moderate to strong seismic excitation [167].

The bending effect of columns and beams connected by specifically designed moment connections are the consequential part in moment-resisting frames withstanding the lateral forces. The columns are accountable for the unified strength and stability of the frame structure and therefore the critical elements. The relative strength to the adjoining beams play an significant role in seismic resistance with regard to manifesting the plastification sequence among respective structural members. Their inelastic deformability, which is largely dependent on the confinement of concrete and the shear capacity, is highly pivotal. Excessive lateral drifts and respective secondary (P-Δ) moments [192] are the key-points which represent the frame as highly susceptible. There are number of old frame buildings which are characterized by masonry infill panels. Albeit the brittle behavior of unreinforced masonry, it is represented as a defective construction material in seismically prone regions, as it may significantly act as masonry infill panel shear walls in controlling deformations and may save non-ductile concrete frames until their elastic limit of such panels is exceeded. Numerous cases have been reported of non-ductile frames surviving intensive seismic ground motions by virtue of the involvement of masonry infill walls, especially when the wall ratio is high. This modifier, based on the structural system of the building, will be considered as $C1$, $C2$, or $C3$.

3.3.2.2 Vertical Irregularity (VI)

The vertical irregularities unfavorably affect the load transfer between structural members, and in some cases, they become the significant parameter responsible for the damage. Therefore, their contribution to the seismic performance must be taken into account. Vertical irregularity often exists in buildings because of the design-process architectural and operational requirements, or possible errors and changes during the construction phase, and due to changes in building use throughout its life. If during observation survey any of the irregularities such as steps in elevation view, inclined walls, buildings on the hill, discontinuity in shear walls, soft story, buildings with short columns, weak columns and strong beams, and any possible modifications introduced to the primary structural system were identified, then this modifier should be considered as *yes*, if present, or *no* otherwise.

3.3.2.3 Plan Irregularity (PI)

The structural eccentricity of a building is due to the irregularity in the plan of the structure. An overall torsion effect is caused by the distance between the centers of mass and stiffness [127]. Therefore, it is better to design buildings with a symmetrical plan layout. Because, lack of symmetry in strength and stiffness along the perimeter of the building, re-entrant corners, and the eccentricity of mass relative to the center of rigidity give rise to torsion. If any of the irregularities like buildings with re-entrant corners (L, T, U, E, + or other irregular building plan), buildings with large lateral resistance in one direction but not in the other direction, or eccentric stiffness in the plan were identified, then this modifier should be acknowledged as *yes*, if present, or *no* otherwise.

3.3.2.4 Number of Story

The number of story is one of the important damage-inducing parameters introduced by Yakut et al. [209], and it is useful to compute the fundamental period (T_l) of the building [166]. In this study, depending on the number of stories above the ground level it should be considered as *short* for 1 to 3 stories, *medium* for 4 to 6 stories, and *tall* for stories > 6 [96]. it is good to know that the majority of the residential and commercial buildings in Turkey have 4 to 7 stories [16] as the scope of this study is short- to medium-rise buildings.

3.3.2.5 Construction Quality (CQ)

Seismic design, quality of construction, materials used, and workmanship determine the response of the buildings to seismic events [192]. Poor quality of construction and materials was reported for some earthquakes [47]; therefore, it is an important parameter to be taken into account. Many reasons lead to poor construction quality, such as corruption of contractors, construction errors, improper construction procedures, ignoring the engineering plans, supplement of low-quality material and concrete, and use of non-seismic hooks and improper seismic detailing. According to Yakut [208], the construction quality is evaluated qualitatively as *poor*, *average*, and *good*.

3.3.2.6 Year of Construction (YC)

Year of construction is an important factors because it is directly related to the strength deterioration of building, released seismic code and the useful life of a building [134]. This parameter can be collected from the engineering, interview with owner or as-built documents. The YC can be classified into five distinct states [78, 88]: *low code (YC ≤ 1944)*, *moderately low code (1944 <YC< 1975)*, *moderate code (1975 ≤ YC < 1998)*, *moderately high code (1998 ≤ YC < 2007)*, and *high code (YC ≥ 2007)*. It should be noted that the threshold values are selected as representatives of Turkey's practice. Therefore, the threshold values need to be adjusted for applications that involve specific geographic location and construction practice. We normalize this parameter interval to [0,1] interval. For this purpose, after partitioning year of construction to 5 parts, then transformation can be done as follows:

- 2007-1944 = 63 years
- Region transition:
  - (YC ≤ 1944) → 0 center of first region (MF1),
  - (1944 <YC< 1975) → (1975-1944)/63= 31/63 = 0.49 → 0.49/2 = 0.245 Center of second region (MF2),
  - (1975 ≤ YC < 1998) → (1998-1975)/63= 23/63 = 0.36 → 0.36/2 = 0.18 → 0.49+0.18 = 0.67 Center of third region (MF3),
  - (1998 ≤ YC < 2007) → (2007-1998)/63= 9/63=0.14 → 0.14/2=0.07 0.49+0.36+0.07=0.92 Center of fourth region (MF4),
  - (YC ≥ 2007) → 1 Center of fifth region (MF5).

Therefore, the normalization of YC will be:

$$YC = \frac{x - 1944}{2007 - 1944} \tag{3.18}$$

where, x is the construction year of the observed building.

3.3.3 Earthquake Hazard Safety Index of building I^{EHS}

By integrating seismic site condition index I^{SSC} and building vulnerability index I^{BV}, the I^{EHS} value is computed. Generally, a building that has a high I^{SSC} may suffer negligibly or almost without damage if designed properly following building codes that are based on contemporary design concepts. On the other hand, if a building has a low I^{SSC} and was designed using older design codes may not be damaged even if it does not comply with the proper seismic design practices. The damage (safety) is classified into five discrete stages: *No damage (D_1)*, *Low damage (D_2)*, *Moderate damage (D_3)*, *Severe damage (D_4)*, and *Collapse (D_5)*. The description of damage states and recommended decision are illustrated in the Table 3.3.

Table 3.3: Description of damage levels and recommended decision (adopted from [12, 136])

Damage state	Description	Decision
No damage (D_1)	No damage, small cracks	Safe, no evacuation needed
Low damage (D_2)	Isolated non-structural damage, cracks in the interior walls or ceilings, damage in water lines, etc.	Slightly safe, might need small repair
Moderate damage (D_3)	Significant non-structural damage and slight structural damage	Moderate safe, needs repair and retrofitting
Severe damage (D_4)	Heavy non-structural damage and important structural damage	Slightly dangerous, need immediate repair and strengthening
Collapse (D_5)	Collapsed buildings or condemned to demolition	Dangerous, evacuation and demolish needed

3.3.4 Building Importance/Exposure Phase

Building importance/exposure index I^{IE} is used to quantify expected human loss, preparation and planning for emergency and rescue services for a given earthquake. The expected loss can be direct physical damage (general building stock, emergency equipment), casualties, economic loss, and social impact [139]. While building codes primarily target life safety (casualties) and post-disaster use (e.g., emergency facility), economical considerations also play an essential role in assessing building importance. For instance, besides the fatalities, the impact of Bingöl and Düzce earthquakes on the economy was high [177, 210]. The Consequence of failure (CoF) is based on reviewing and ranking the potential consequences for the equipment, personnel, environment, and so forth. in the event of equipment failure. Therefore, the building importance/exposure index I^{IE} is computed by integrating *building use*, *occupancy* and for the post-earthquake services may use *time of event* to prioritize and preparation in case of building failure.

3.3.4.1 Building Use

The use of the building should indicate the benefits of the building after a disaster and the associated possible damage that can be tolerated. The FEMA 450 [41] guideline for the design of new buildings specifies three distinct groups. The first level is Immediate Occupancy (IO) performance level, where the level of damage tolerated is negligible and light. Buildings required for post-earthquake services for instance, hospitals, fire rescue, and police stations, communication centers, fall under the IO category. The second level is Life Safety (LS), where a moderate damage state is tolerated. Typically, buildings used for public assembly, schools, structures with more than 5000 people capacity fall under LS. In this category, the structural failure is not imminent, and life safety can be ensured. Any other structure that is not classified as IO or LS is assigned to a low importance building category. Severe and complete collapses are not acceptable levels of performance.

3.3.4.2 Occupancy

In the context of building construction and building codes, "occupancy" refers to the use or intended use of a building or part of a building to protect or support people, animals or property [19]. The occupancy of a building is important to infer possible casualties and provide enough services in case of earthquake induced damage. The tolerance level for causalities is a social value judgment [106, 105]. The occupancy (described by the number of people) is divided into 4 discrete groups; L(0-10), M(11-50), H(51-100), and VH(more than 100).

3.3.4.3 Time of Event

Time is one of the critical factors of loss/death rates, which depends on the time of an earthquake event and the usage of buildings. For example, if an earthquake strikes the residential and school buildings during the day time, the priority of rescue service and inspection should be on school buildings and then residential, while if it struck at midnight, there is not necessary to give service to schools. The time in 24 hours is divided into 3 discrete groups: *A (7:00-14:00)*, *B (14:00-21:00)*, and *C (21:00-7:00)*.

3.3.5 Earthquake Risk Index I^{ER}

In the Figure 3.9, the earthquake risk index I^{ER} is quantified by aggregating the earthquake hazard safety index I^{EHS} and importance/exposure index I^{IE}. The final I^{ER} value is in a unit interval $I^{ER} \in [0, 1]$. For decision making purpose, however, the I^{ER} value can be converted into a linguistic constant. In this thesis, four linguistic constants are considered for final decision-making purpose: *Low*, *Moderate*, *High* and *Very high*. The I^{ER} values are categorized into [0, 0.2]; [0.2, 0.4], [0.4, 0.6] and [0.6, 1.0].

3.4 Proposed Fuzzy Model for RVS

Fuzzy logic provides a language with semantics to translate qualitative knowledge into numerical reasoning. The strength of fuzzy logic is that it can integrate descriptive (linguistic) and numerical data into a fuzzy model and use approximate reasoning algorithms to propagate the uncertainties throughout the decision process. The fuzzy inference system (FIS) contains three basic features [215]:

- Linguistic variables instead of, or in addition to, numerical variables;
- Relationships between the variables in terms of IF-THEN rules (rule-based); and
- An inference mechanism that uses approximate reasoning algorithms to formulate relationships.

This thesis focuses on the use of Mamdani inference, which is one of the most popular techniques in applied fuzzy logic. As described earlier in this chapter, Mamdani systems are composed of IF-THEN rules of the form "IF X is A THEN Y is B". The IF part "X is A" is called the *antecedent* of the rule, and the THEN part "Y is B" is called the *consequent* of the rule. Most often, Mamdani systems are composed of several IF-THEN rules and presenting such as:

- $\tilde{R}_1$ = IF x_1 is A_1 THEN Y_1 is B_1
- $\tilde{R}_2$ = IF x_2 is A_2 THEN Y_2 is B_2
- ...
- $\tilde{R}_n$ = IF x_n is A_n THEN Y_n is B_n

where $\tilde{R}_i$ (i= 1,..., n) is the i^{th} rule. Due to the proposed method's hierarchical structure, the number of rules has been significantly reduced in this study. There must be 162,000 rules in a typical way, but only 141 rules have been defined in the proposed method, leading to faster computation, easy to understand, and explainable model.

3.4.1 Inference Mechanism

Mamdani's inference mechanism consists of three connectives: the aggregation of antecedents in each rule, implication, and aggregation of the rules. The operators performing the connectives distinguish the type of fuzzy inferencing. The AND and OR operators are selected for fuzzy operators in the proposed model. In this thesis, the minimum and maximum operators are used in the case of fuzzy AND and fuzzy OR operators, respectively.

3.4.2 Fuzzification, Rules and Diffuzification

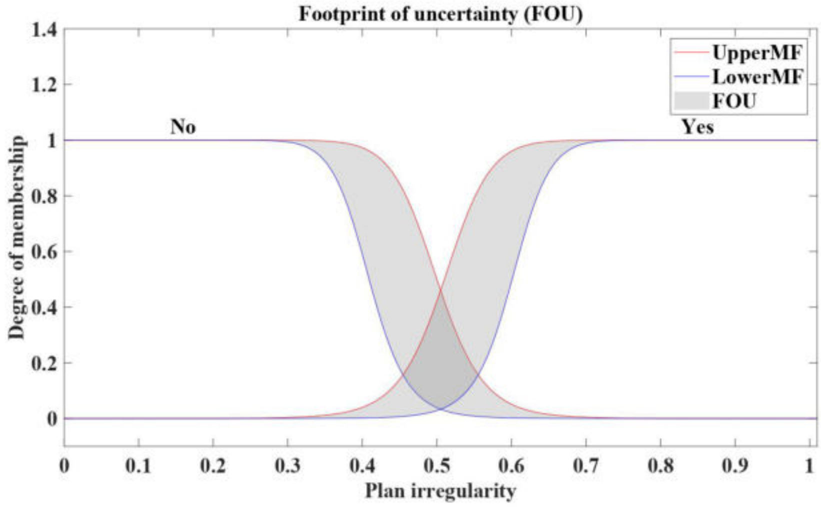
In proposed hierarchy fuzzy modeling, each subsection (e.g., building parameters or soil type) converts to a fuzzy model. The following sections explain fuzzification, rules, and defuzzification for different fuzzy models inside our methodology.

3.4.2.1 Modeling Increase in Demand ($R1$)

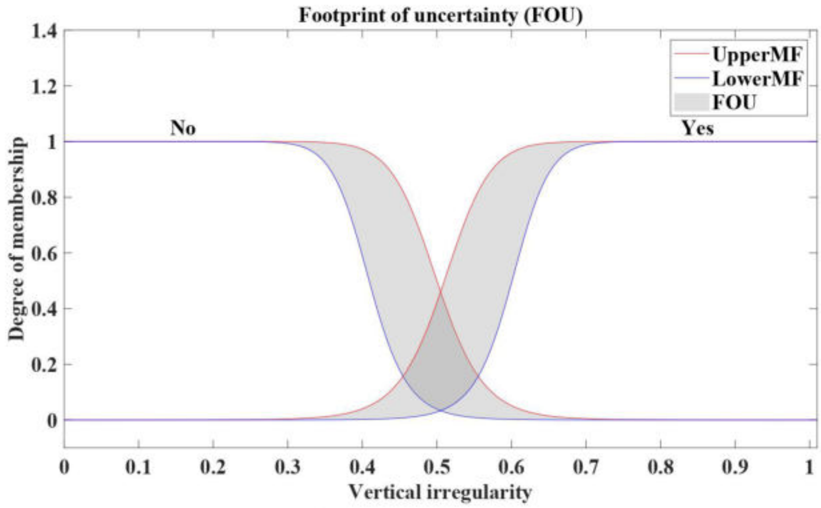
In Table 3.4, the first column presents the performance modifiers under consideration (e.g., vertical irregularity). The fuzzification and output fuzzy set of corresponding R_i are provided in columns 2 and 3, respectively. Also, the related MFs are plotted in Figure 3.11. Table 3.5 provides the fuzzy rule base for increase in demand. In the below tables, the vertical irregularity (VI), Plan irregularity (PI), No. of story (NS) as performance modifiers for Increase in demand (ID) are presented.

Table 3.4: Performance modifiers for increase in demand (ID)

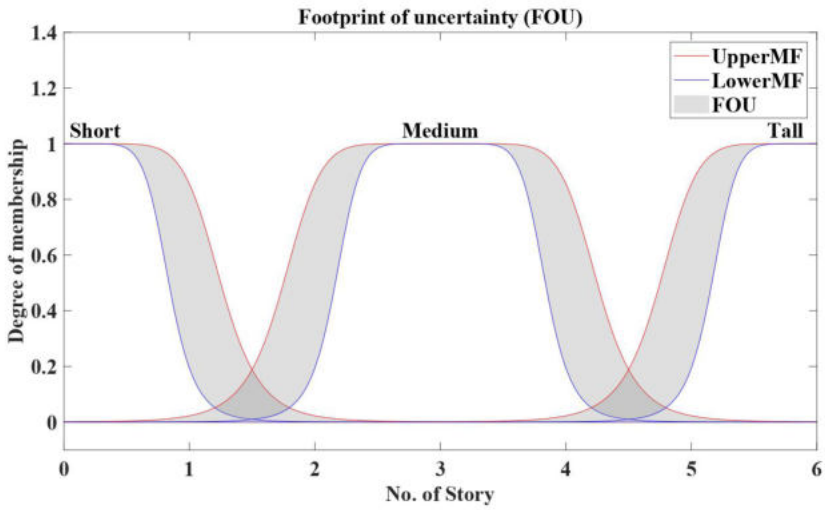
	$R1$	
Parameter	**Fuzzification**	**Output fuzzy set**
Vertical Irregularity	{Yes, No}	
Plan Irregularity	{Yes, No}	{L, M, H}
No. of story	{Short, Medium, Tall}	



(a) Plan irregularity

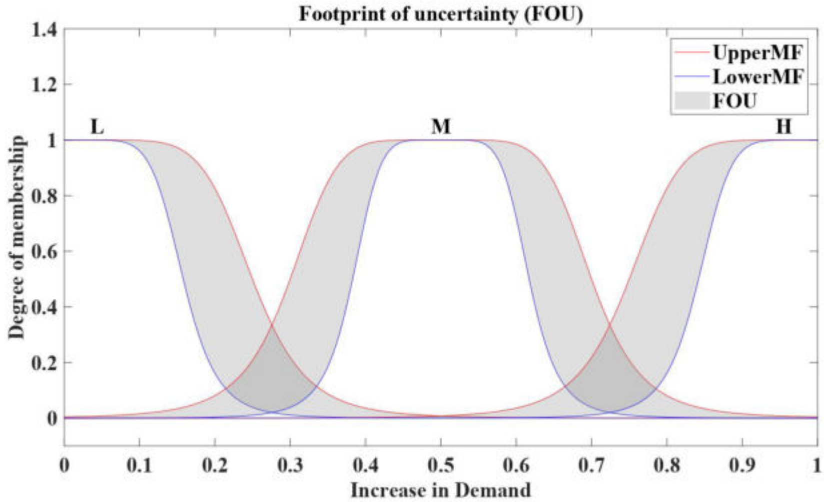


(b) Vertical irregularity



(c) No. of Story

Figure 3.11: Generalized bell-shaped membership function for input variables (a) plan irregularity, (b) vertical irregularity, (c) No. of story



(a) Increase in demand

Figure 3.12: Generalized bell-shaped membership function for output (a) increase in demand

Table 3.5: Fuzzy rule base for increase in demand (ID)

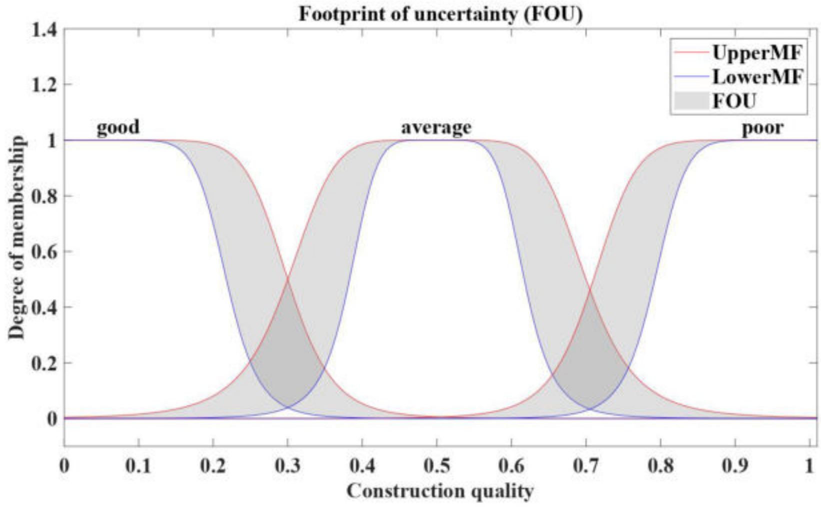
	R_1			
Rule i	**PI**	**VI**	**NS**	**ID**
1	N	N	S	L
2	N	N	M	L
3	N	N	T	M
4	N	Y	S	L
5	N	Y	M	M
6	N	Y	T	H
7	Y	N	S	L
8	Y	N	M	M
9	Y	N	T	H
10	Y	Y	S	M
11	Y	Y	M	H
12	Y	Y	T	H

3.4.2.2 Modeling Decrease in Resistance ($R2$)

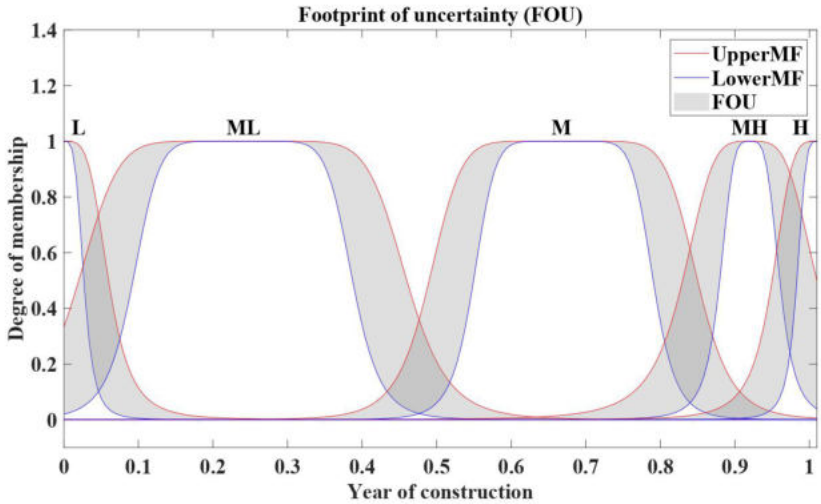
In Table 3.6, the first Column presents the performance modifiers under consideration. The fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Also, the related MFs are plotted in Figure 3.13. Table 3.7 provides the fuzzy rule base for decrease in resistance. In the below tables, the year of construction (YC) and construction quality (CQ) as performance modifiers for decrease in resistance (DR) are presented.

Table 3.6: Performance modifiers for decrease in resistance (DR)

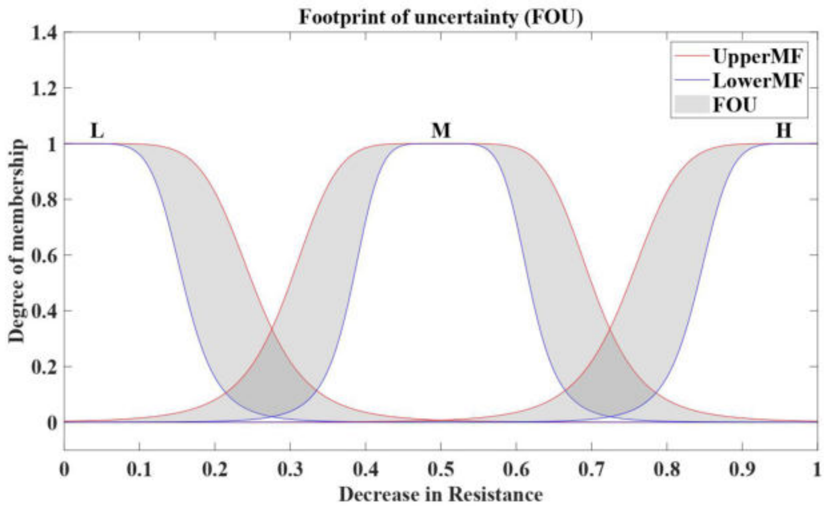
	$R2$	
Parameter	**Fuzzification**	**Output fuzzy set**
Construction quality	{good, average, poor}	{L, M, H}
Year of construction	{L, ML, M, MH, H}	



(a) Construction quality



(b) Year of construction



(c) Decrease in resistance

Figure 3.13: Generalized bell-shaped membership function for input variables (a) construction quality, (b) year of construction, and output (c) increase in demand

Table 3.7: Fuzzy rule base for decrease in resistance (DR)

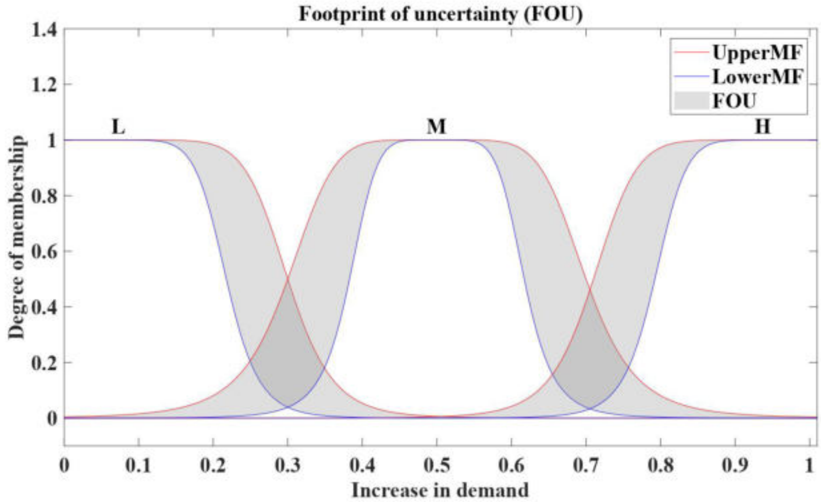
*R*2			
Rule i	**CQ**	**YC**	**DR**
1	G	L	H
2	G	ML	M
3	G	M	M
4	G	MH	L
5	G	H	L
6	A	L	H
7	A	ML	H
8	A	M	M
9	A	MH	M
10	A	H	L
11	P	L	H
12	P	ML	H
13	P	M	H
14	P	MH	H
15	P	H	M

3.4.2.3 Modeling Structural Deficiency ($R3$)

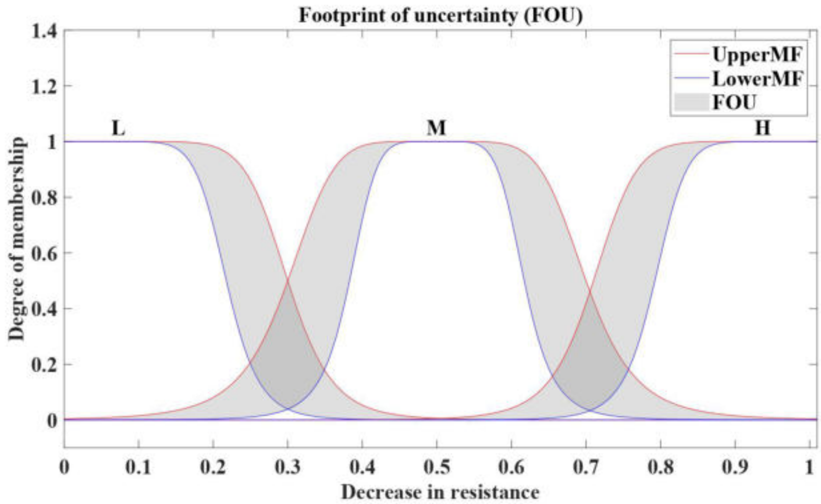
In Table 3.8, the first Column presents the performance modifiers under consideration. The fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Also, the related MFs are plotted in Figure 3.14. Table 3.9 provides the fuzzy rule base for structural deficiency. In the below tables, the increase in demand (ID) and decrease in resistance (DR) as performance modifiers for structural deficiency (SD) are presented.

Table 3.8: Performance modifiers for structural deficiency (SD)

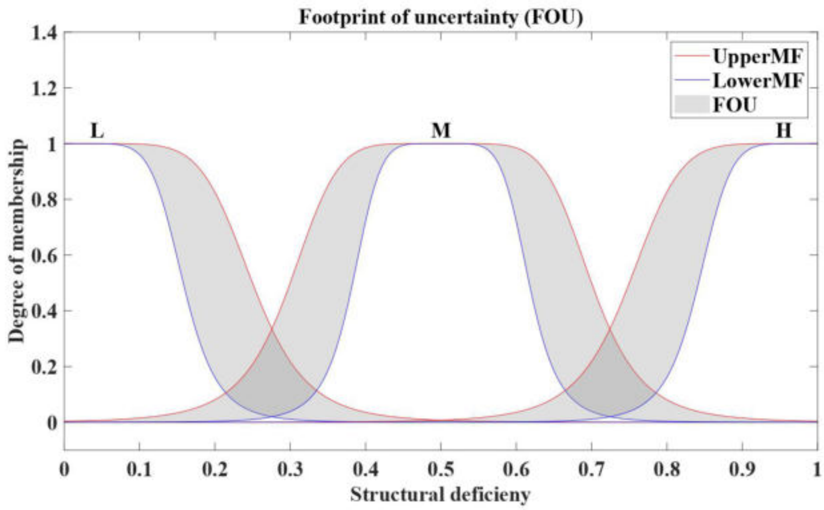
*R*3		
Parameter	**Fuzzification**	**Output fuzzy set**
Increase in demand	{L, M, H}	{L, M, H}
Decrease in resistance	{L, M, H}	



(a) Increase in demand



(b) Decrease in resistance



(c) Structural deficiency

Figure 3.14: Generalized bell-shaped membership function for input variables (a) increase in demand, (b) decrease in resistance, and output (c) structural deficiency

Table 3.9: Fuzzy rule base for structural deficiency (SD)

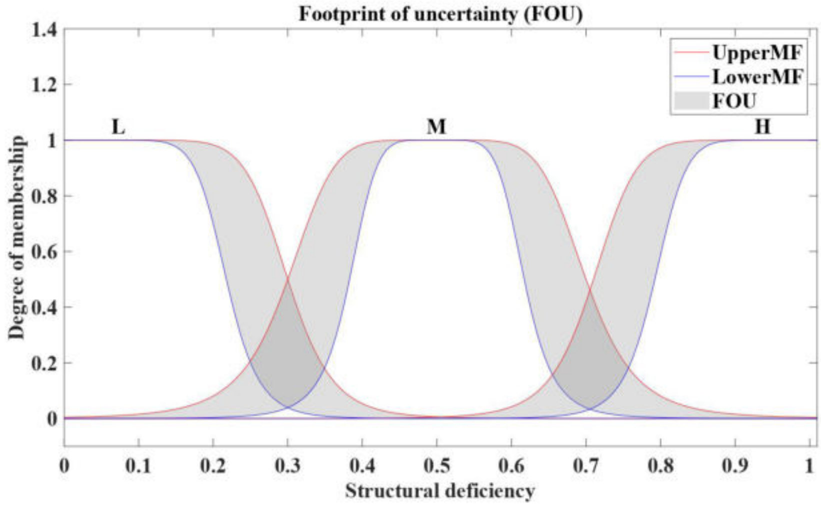
*R*3			
Rule i	**ID**	**DR**	**SD**
1	L	L	L
2	L	M	M
3	L	H	M
4	M	L	L
5	M	M	M
6	M	H	H
7	H	L	M
8	H	M	H
9	H	H	H

3.4.2.4 Modeling Building Vulnerability Index ($R4$)

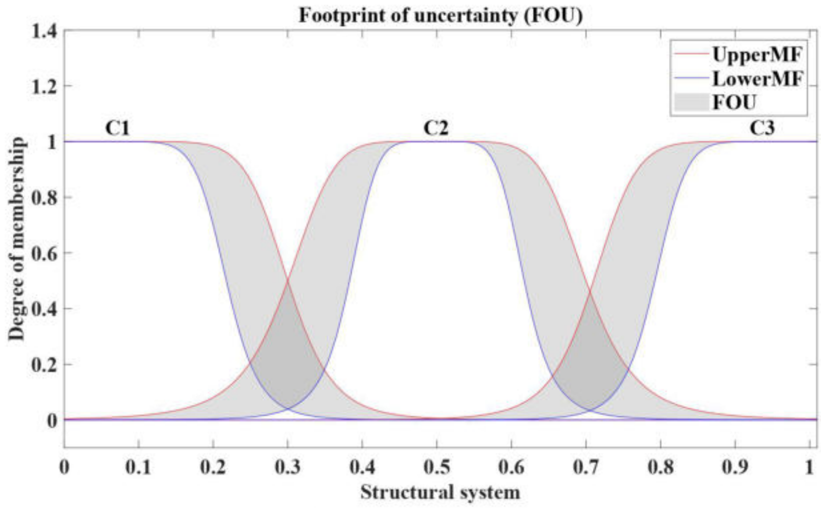
In Table 3.10, the first column presents the performance modifiers under consideration. The fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Also, the related MFs are plotted in Figure 3.15. Table 3.11 provides the fuzzy rule base for building vulnerability. In the below tables, the structural deficiency (SD) and structural system (SS) as performance modifiers for building vulnerability index (I^{BV}) are presented.

Table 3.10: Performance modifiers for building vulnerability index (I^{BV})

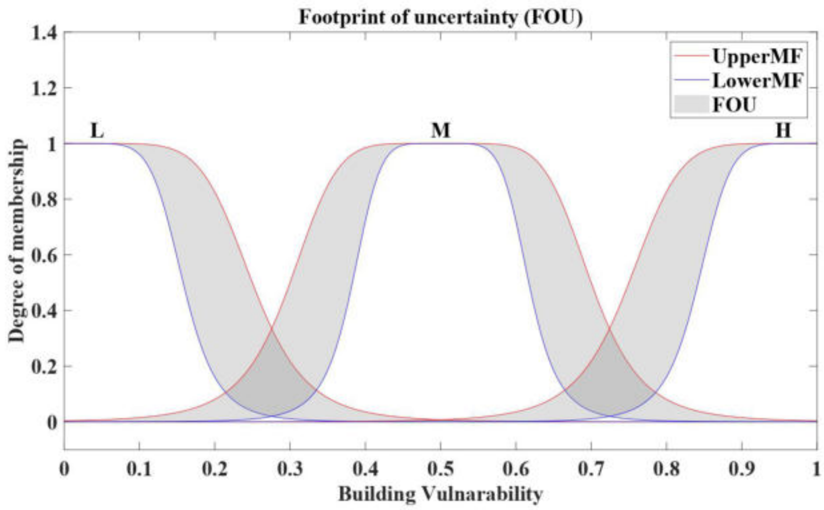
*R*4		
Parameter	**Fuzzification**	**Output fuzzy set**
Structural deficiency	{L, M, H}	{L, M, H}
Structural system	{C1, C2, C3}	



(a) Structural deficiency



(b) Structural system



(c) Building vulnerability

Figure 3.15: Generalized bell-shaped membership function for input variables (a) structural deficiency, (b) structural system, and output (c) building vulnerability

Table 3.11: Fuzzy rule base for building vulnerability index (I^{BV})

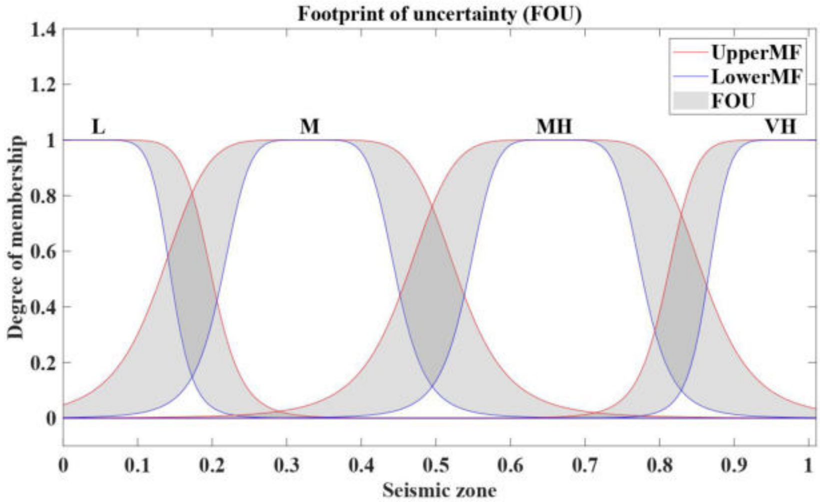
$R4$			
Rule i	**SD**	**SS**	I^{BV}
1	C1	L	M
2	C1	M	H
3	C1	H	H
4	C2	L	L
5	C2	M	L
6	C2	H	M
7	C3	L	L
8	C3	M	M
9	C3	H	H

3.4.2.5 Modeling Seismic Site Condition Index ($R5$)

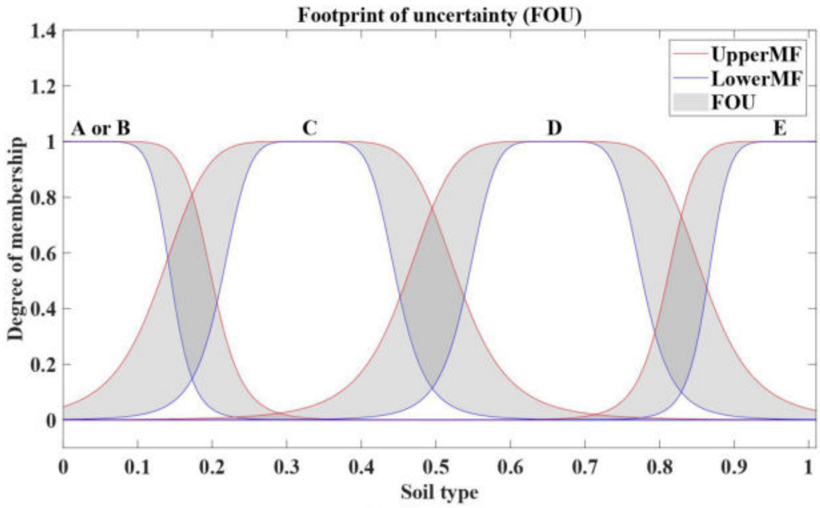
In Table 3.12, the first Column presents the performance modifiers under consideration. The fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Also, the related MFs are plotted in Figure 3.16. Table 3.13 provides the fuzzy rule base for seismic site condition. In the below tables, the seismic zone (SZ) and soil type (ST) as performance modifiers for seismic site condition index (I^{SSC}) are presented.

Table 3.12: Performance modifiers for seismic site condition index (I^{SSC})

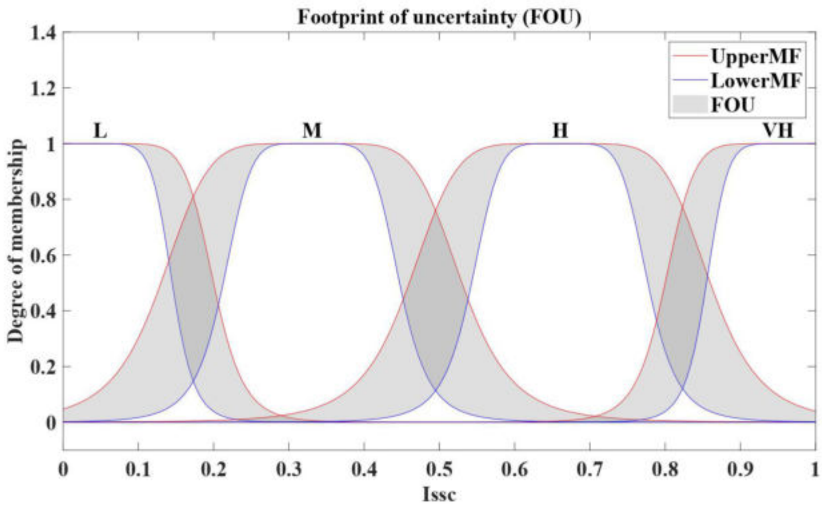
$R5$		
Parameter	**Fuzzification**	**Output fuzzy set**
Seismic zone	{L, M, MH, H and VH]	{L, M, H, VH}
Soil type	{A or B, C, D, E}	



(a) Seismic zone



(b) Soil type



(c) Seismic site condition

Figure 3.16: Generalized bell-shaped membership function for input variables (a) seismic zone, (b) soil type, and output (c) seismic site condition

Table 3.13: Fuzzy rule base for seismic site condition index (I^{SSC})

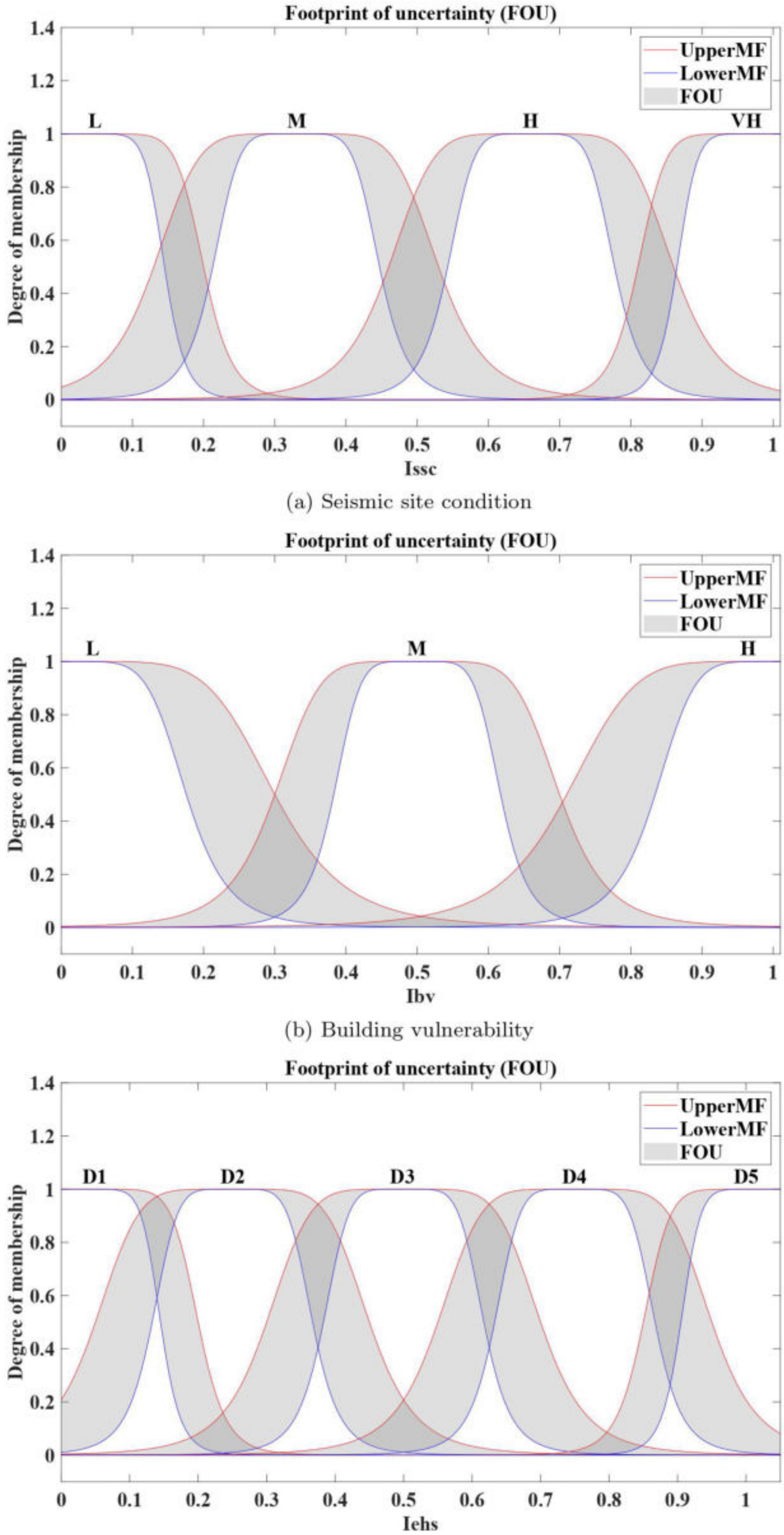
	$R5$		
Rule i	**ST**	**SZ**	I^{SSC}
1	A or B	L	L
2	A or B	M	L
3	A or B	MH	M
4	A or B	H and VH	M
5	C	L	L
6	C	M	M
7	C	MH	H
8	C	H and VH	VH
9	D	L	M
10	D	M	M
11	D	MH	H
12	D	H and VH	VH
13	E	L	M
14	E	M	H
15	E	MH	VH
16	E	H and VH	VH

3.4.2.6 Modeling Earthquake Hazard Safety Index ($R6$)

The first column of Table 3.14 presents the performance modifiers under consideration meanwhile, fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Also, the related MFs are illustrated in Figure 3.17. Table 3.15 shows the fuzzy rule base for earthquake hazard safety index. In the below tables, the seismic site condition index (I^{SSC}) and building vulnerability index (I^{BV}) as performance modifiers for earthquake hazard safety index (I^{EHS}) are presented.

Table 3.14: Performance modifiers for seismic site condition (SSC)

	$R6$	
Parameter	**Fuzzification**	**Output fuzzy set**
I^{SSC}	{L, M, H, VH}	{D1, D2, D3, D4, D5}
I^{BV}	{L, M, H}	



(a) Seismic site condition

(b) Building vulnerability

(c) Earthquake hazard safety

Figure 3.17: Generalized bell-shaped membership function for input variables (a) seismic site condition, (b) building vulnerability, and output (c) earthquake hazard safety

Table 3.15: Fuzzy rule base for earthquake hazard safety index (I^{EHS})

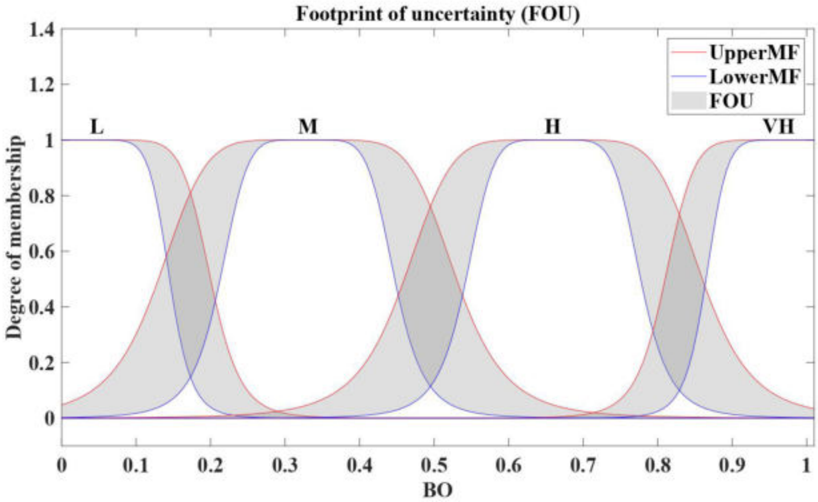
R6			
Rule i	I^{SSC}	I^{BV}	I^{EHS}
1	L	L	D1
2	L	M	D1
3	L	H	D2
4	M	L	D2
5	M	M	D3
6	M	H	D4
7	H	L	D2
8	H	M	D4
9	H	H	D5
10	VH	L	D3
11	VH	M	D4
12	VH	H	D5

3.4.2.7 Modeling Building Importance/Exposure ($R7$)

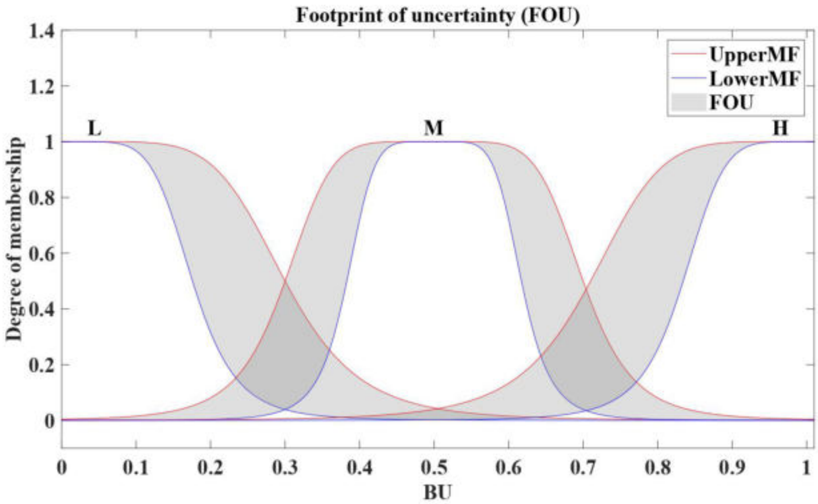
Similar to previous parts, the first column of Table 3.16 presents the performance modifiers under consideration meanwhile, fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Moreover, the related MFs are presented in Figure 3.18. Table 3.17 shows the fuzzy rule base for building importance/exposure index. In the below tables, the building occupancy (BO) and building use (BU) as performance modifiers for building importance/exposure index (I^{IE}) are presented.

Table 3.16: Performance modifiers for building importance/exposure index (I^{IE})

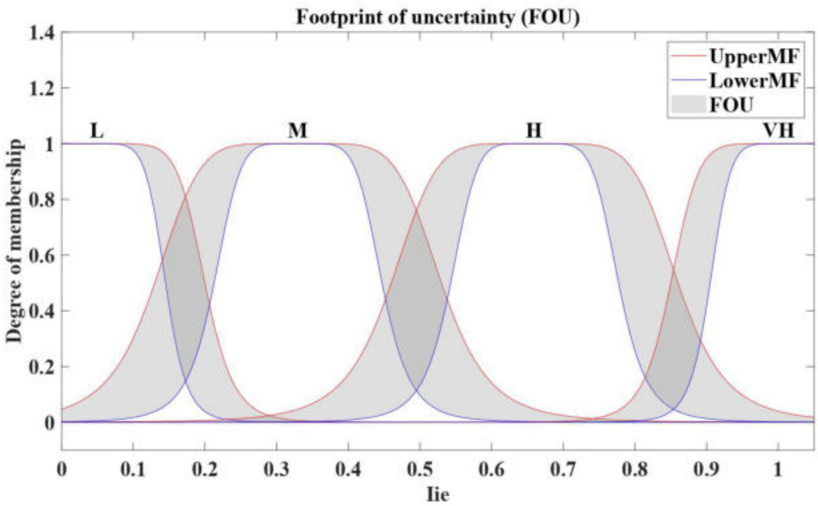
R7		
Parameter	**Fuzzification**	**Output fuzzy set**
BO	{L, M, H, VH}	{L, M, H, VH}
BU	{L, M, H}	



(a) Building occupancy



(b) Building use



(c) Building importance/exposure

Figure 3.18: Generalized bell-shaped membership function for input variables (a) building occupancy, (b) building use, and output (c) building importance/exposure index (I^{IE})

Table 3.17: Fuzzy rule base for building importance/exposure index (I^{IE})

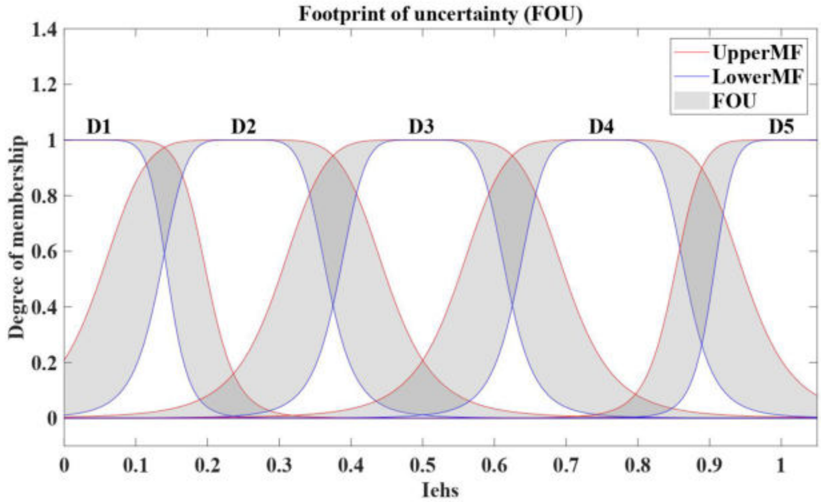
R7			
Rule i	**BO**	**BU**	I^{IE}
1	L	L	L
2	L	M	L
3	L	H	M
4	M	L	L
5	M	M	M
6	M	H	H
7	H	L	M
8	H	M	H
9	H	H	VH
10	VH	L	M
11	VH	M	H
12	VH	H	VH

3.4.2.8 Modeling Earthquake Risk Index($R8$)

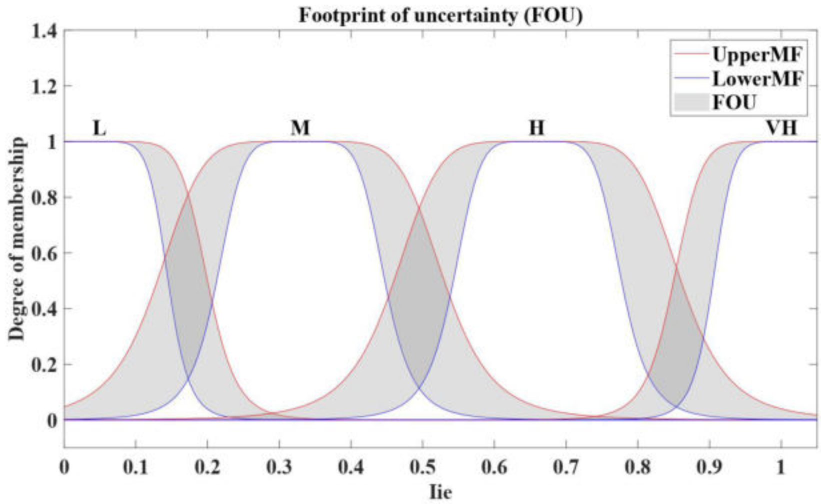
The first column of Table 3.18 presents the performance modifiers under consideration meanwhile, fuzzification and output fuzzy set of correspond R_i are provided in columns 2 and 3, respectively. Also, the related MFs are illustrated in Figure 3.19. Table 3.19 shows the fuzzy rule base for earthquake risk index. In the below tables, the earthquake hazard safety index (I^{EHS}) and building importance/exposure index (I^{IE}) as performance modifiers for earthquake risk index (I^{ER}) are presented.

Table 3.18: Performance modifiers for earthquake risk index (I^{ER})

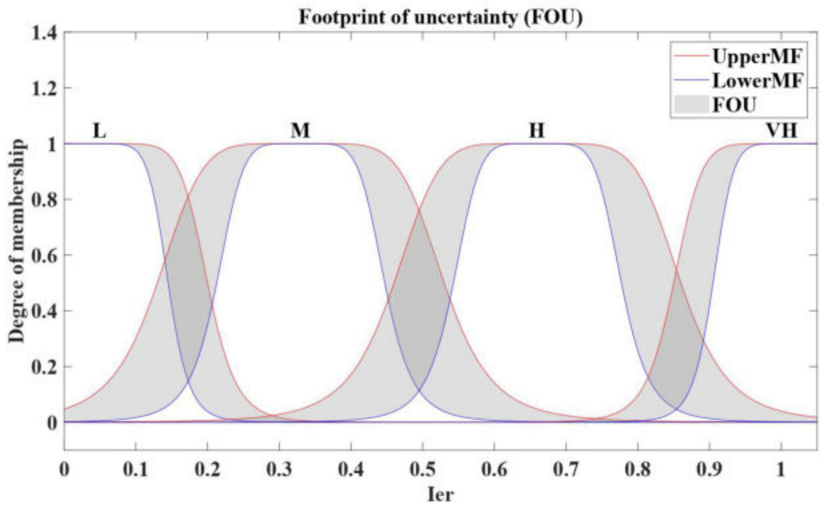
R8		
Parameter	**Fuzzification**	**Output fuzzy set**
I^{EHS}	{D1, D2, D3, D4, D5}	{L, M, H, VH}
I^{IE}	{L, M, H, VH}	



(a) Earthquake hazard safety



(b) Building importance/exposure



(c) Earthquake risk

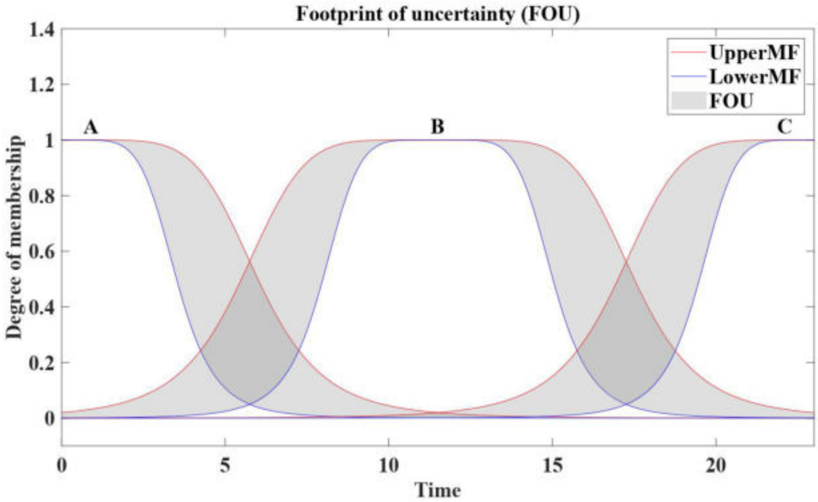
Figure 3.19: Generalized bell-shaped membership function for input variables (a) earthquake hazard safety index, (b) building importance/exposure index, and output (c) earthquake risk index (I^{ER})

Table 3.19: Fuzzy rule base for earthquake risk index (I^{ER})

$R8$			
Rule i	I^{EHS}	I^{IE}	I^{ER}
1	D1	L	L
2	D1	M	L
3	D1	H	M
4	D1	VH	M
5	D2	L	L
6	D2	M	L
7	D2	H	M
8	D2	VH	H
9	D3	L	L
10	D3	M	M
11	D3	H	H
12	D3	VH	H
13	D4	L	L
14	D4	M	M
15	D4	H	H
16	D4	VH	VH
17	D5	L	M
18	D5	M	H
19	D5	H	VH
20	D5	VH	VH

3.4.2.9 Modeling Earthquake Risk at The Time of Event ($R7(time)$)

The time of an earthquake during the day can be an important factor in the number of injuries, prioritizing rescue services and, quickly estimating loss and damage. In this thesis, not as the main objective, but as a recommendation, this factor has been introduced. In case of use, the time of the event will be added to the fuzzy rules R_7 in Table 3.17 and will be as it is shown in Table 3.20. The MFs regarding the time of event has been presented in Figure 3.20. Then, proceed with the I^{EHS} in the R_8 to achieve a new I^{ER} according to the time of event.



(a) Time of event

Figure 3.20: Generalized bell-shaped membership function for (a) time of event

Table 3.20: Fuzzy rule base for building importance/exposure index (I^{IE}) by considering time of event

$R7(time)$				
Rule i	**BO**	**BU**	**TE**	I^{IE}
1	L	L	A	L
2	L	L	B	L
3	L	L	C	L
4	L	M	A	L
5	L	M	B	L
6	L	M	C	M
7	L	H	A	M
8	L	H	B	M
9	L	H	C	M
10	M	L	A	M
11	M	L	B	L
12	M	L	C	L
13	M	M	A	M
14	M	M	B	M
15	M	M	C	H
16	M	H	A	H
17	M	H	B	H
18	M	H	C	M
19	H	L	A	H
20	H	L	B	M
21	H	L	C	L
22	H	M	A	H
23	H	M	B	H
24	H	M	C	VH
25	H	H	A	VH
26	H	H	B	VH
27	H	H	C	H
28	VH	L	A	H
29	VH	L	B	H
30	VH	L	C	M
31	VH	M	A	H
32	VH	M	B	VH
33	VH	M	C	VH
34	VH	H	A	VH
35	VH	H	B	VH
36	VH	H	C	VH

3.4.3 Type Reduction and Defuzzification

For all the above models there must be a numerical constant output which is the input for next fuzzy model in our proposed fuzzy hierarchy model. For example, both increase in demand and decrease in resistance outputs are type-2 fuzzy sets. However, these outputs are the inputs for structure deficiency model. Therefore, here a type reduction and defuzzification procedure is required. The classical IT2 fuzzy system, has separate type-reduction and defuzzification steps. Type-reduction combines, the firing interval of the rules, and the corresponding rule consequents, to form a type-1 fuzzy set. There are many type-reduction methods [112], but the most commonly used one is centeroid type-reducer [34]. Several efficient methods have been proposed for computing centroid or center of sets, including well-known Karnik-Mendel (KM) algorithm [89]. For further information and comprehensive description refer to [115, 108]. Type reduction speed depends on the used language programming. In this thesis, an Enhanced Karnik-Mendel (EKM) algorithm is used for type-reduction procedure. Once the type reduction output fuzzy sets are obtained, the final crisp output is a centroid of these fuzzy sets whose formula is given in Eq. 3.17.

3.5 An Example to Illustrate Procedure of Proposed IT2FLS for RVS

Here, an example of building with a specific soil type and region is considered to illustrate different steps of the proposed method. The selected building is a real building located in Düzce city of Turkey and affected by the 1999 earthquake. The data of buildings were collected by a walk-down survey. Table 3.21 presents the building performance modifiers and the state of the selected building (No.121).

Table 3.21: Information of selected building No. 47 to illustrate an example

Vulnerability parameter	**Building information**
Number of stories (NS)	4
Vertical irregularity (VI)	Yes
Plan irregularity (PI)	No
Year of construction (YC)	1978
Construction quality (CQ)	Average
Building Structural system (SS)	C3
Soil Type (ST)	D
Seismic Zone (SZ)	Very high
Building occupancy (BO)	Medium
Building use (BU)	Medium
Observed Damage (OD)	Severe

3.5.1 Step 1: Transformation (Initialization)

The primary step of the evaluation process is transforming the parameters. Table 3.22 shows the transformed value of parameters, which are related to the fuzzy model $R1$.

Table 3.22: Transformation of parameters related to the fuzzy model $R1$

	R_1	
Vulnerability parameter	**Building information**	**Transformed value**
Number of stories (NS)	4	4
Vertical irregularity (VI)	Yes	0.9
Plan irregularity (PI)	No	0.1

3.5.2 Step 2: Fuzzification

In this step the input values of the $R1$ model will be fuzzified. Here all membership functions are considered to be bell-shaped. Therefore, all membership functions are as follows:

$$\mu = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}} \tag{3.19}$$

where a defines the width of the membership function, where a larger value creates a wider membership function. b defines the shape of the curve on either side of the central plateau, where a larger value creates a more steep transition and c defines the center of the membership function.

Number of Stories (NS):

$$(S,\ M,\ T) = \begin{cases} (\overline{\mu}_{\tilde{S}}(x'),\ \overline{\mu}_{\tilde{M}}(x'),\ \overline{\mu}_{\tilde{T}}(x')) = (\frac{1}{1+|\frac{x}{1.25}|^8},\ \frac{1}{1+|\frac{x-3}{1.25}|^8},\ \frac{1}{1+|\frac{x-6}{1.25}|^8}) \\ \\ (\underline{\mu}_{\tilde{S}}(x'),\ \underline{\mu}_{\tilde{M}}(x'),\ \underline{\mu}_{\tilde{T}}(x')) = (\frac{1}{1+|\frac{x}{1.25}|^8},\ \frac{1}{1+|\frac{x-3}{1.25}|^8},\ \frac{1}{1+|\frac{x-6}{1.25}|^8}) \end{cases} \tag{3.20}$$

Now, the membership grade of Number of Stories (NS) for the sample building can be calculated as:

$$\left\{\underline{\mu}_{\tilde{S}}^{N}(4),\ \overline{\mu}_{\tilde{S}}^{N}(4)\right\} = \left\{\frac{1}{1+|\frac{4}{0.75}|^8},\ \frac{1}{1+|\frac{4}{1.25}|^8}\right\} \approx \{0,0\} \tag{3.21}$$

$$\left\{\underline{\mu}_{\tilde{M}}^{N}(4),\ \overline{\mu}_{\tilde{M}}^{N}(4)\right\} = \left\{\frac{1}{1+|\frac{4-3}{0.75}|^8},\ \frac{1}{1+|\frac{4-3}{1.25}|^8}\right\} \approx \{0.09,\ 0.86\} \tag{3.22}$$

$$\left\{\underline{\mu}_{\tilde{T}}^{N}(4),\ \overline{\mu}_{\tilde{T}}^{N}(4)\right\} = \left\{\frac{1}{1+|\frac{4-6}{0.75}|^8},\ \frac{1}{1+|\frac{4-6}{1.25}|^8}\right\} \approx \{0,\ 0.023\} \tag{3.23}$$

Plan Irregularities (PI):

$$(No,\ Yes) = \begin{cases} (\overline{\mu}_{\tilde{No}}(x'),\ \overline{\mu}_{\tilde{Yes}}(x')) = (\frac{1}{1+|\frac{x}{0.5}|^{16}},\ \frac{1}{1+|\frac{x-1}{0.5}|^{16}}) \\ \\ (\underline{\mu}_{\tilde{No}}(x'),\ \underline{\mu}_{\tilde{Yes}}(x')) = (\frac{1}{1+|\frac{x}{0.4}|^{16}},\ \frac{1}{1+|\frac{x-1}{0.4}|^{16}}) \end{cases} \tag{3.24}$$

Therefore, the membership grade of Plan Irregularity (PI) for the sample building can be calculated as:

$$\left\{\underline{\mu}_{\tilde{No}}^{PI}(0.1),\ \overline{\mu}_{\tilde{No}}^{PI}(0.1)\right\} = \left\{\frac{1}{1+|\frac{0.1}{0.4}|^{16}},\ \frac{1}{1+|\frac{0.1}{0.5}|^{16}}\right\} \approx \{1,1\} \tag{3.25}$$

$$\left\{\underline{\mu}_{\tilde{Yes}}^{PI}(0.1),\ \overline{\mu}_{\tilde{Yes}}^{PI}(0.1)\right\} = \left\{\frac{1}{1+|\frac{0.1-1}{0.4}|^{16}},\ \frac{1}{1+|\frac{0.1-1}{0.5}|^{16}}\right\} \approx \{0,0\} \tag{3.26}$$

Vertical Irregularities (VI):

$$(No,\ Yes) = \begin{cases} (\overline{\mu}_{\tilde{No}}(x'),\ \overline{\mu}_{\tilde{Yes}}(x')) = (\frac{1}{1+|\frac{x}{0.5}|^{16}},\ \frac{1}{1+|\frac{x-1}{0.5}|^{16}}) \\ \\ (\underline{\mu}_{\tilde{No}}(x'),\ \underline{\mu}_{\tilde{Yes}}(x')) = (\frac{1}{1+|\frac{x}{0.4}|^{16}},\ \frac{1}{1+|\frac{x-1}{0.4}|^{16}}) \end{cases} \tag{3.27}$$

Consequently, the membership grade of Vertical Irregularity (VI) for the sample building can be calculated as:

$$\left\{\underline{\mu}_{\tilde{No}}^{VI}(0.9),\ \overline{\mu}_{\tilde{No}}^{VI}(0.9)\right\} = \left\{\frac{1}{1+|\frac{0.9}{0.4}|^{16}},\ \frac{1}{1+|\frac{0.9}{0.5}|^{16}}\right\} \approx \{0,0\} \tag{3.28}$$

$$\left\{\underline{\mu}_{\tilde{Yes}}^{VI}(0.9),\ \overline{\mu}_{\tilde{Yes}}^{VI}(0.9)\right\} = \left\{\frac{1}{1+|\frac{0.9-1}{0.4}|^{16}},\ \frac{1}{1+|\frac{0.9-1}{0.5}|^{16}}\right\} \approx \{1,1\} \tag{3.29}$$

3.5.3 Step 3: Apply Rules (Inference)

After Fuzzification, the next step is to apply rules according to Table 3.5. Based on the sample building, only some of the rules have been fired as $\{\tilde{R}_5$ and $\tilde{R}_6\}$.

- $\tilde{R}_5$: IF PI is No and IF VI is Yes and IF N is M $THEN$ ID is M
- $\tilde{R}_6$: IF PI is No and IF VI is Yes and IF N is T $THEN$ ID is H

Then firing intervals can be computed for antecedent of $\tilde{R}_5$ and $\tilde{R}_6$ as follows:

$$\begin{aligned}
\tilde{R}_5 : f^{\tilde{R}_5} &= \{\underline{f}^{\tilde{R}_5}, \overline{f}^{\tilde{R}_5}\} \\
&= \left\{min\left(\underline{\mu}_{\tilde{No}}^{PI}(0.1),\ \underline{\mu}_{\tilde{Yes}}^{VI}(0.9),\ \underline{\mu}_{\tilde{M}}^{N}(4)\right),\ min\left(\overline{\mu}_{\tilde{No}}^{PI}(0.1),\ \overline{\mu}_{\tilde{Yes}}^{VI}(0.9),\ \overline{\mu}_{\tilde{M}}^{N}(4)\right)\right\} \\
&= \{min(1,\ 1,\ 0.09),\ min(0,\ 1,\ 0.86)\} = \{0.09,\ 0\}
\end{aligned} \tag{3.30}$$

$$\begin{aligned}
\tilde{R}_6 : f^{\tilde{R}_6} &= \{\underline{f}^{\tilde{R}_6}, \overline{f}^{\tilde{R}_6}\} \\
&= \left\{min\left(\underline{\mu}_{\tilde{No}}^{PI}(0.1),\ \underline{\mu}_{\tilde{Yes}}^{VI}(0.9),\ \underline{\mu}_{\tilde{M}}^{N}(4)\right),\ min\left(\overline{\mu}_{\tilde{No}}^{PI}(0.1),\ \overline{\mu}_{\tilde{Yes}}^{VI}(0.9),\ \overline{\mu}_{\tilde{M}}^{N}(4)\right)\right\} \\
&= \{min(1,\ 1,\ 0),\ min(1,\ 1,\ 0.023)\} = \{0,\ 0.023\}
\end{aligned} \tag{3.31}$$

According to Eq.3.14, the output (implication) of $\tilde{R}_5$ and $\tilde{R}_6$ can be calculated as:

$$\tilde{R}_5\ output:\ \mu_{\tilde{B}}^{\tilde{R}_5}(y) = \left\{min\left(\underline{f}^{\tilde{R}_5},\ \mu_M^{ID}(y)\right),\ min\left(\overline{f}^{\tilde{R}_5},\ \mu_M^{ID}(y)\right)\right\} \tag{3.32}$$

$$\tilde{R}_6\ output:\ \mu_{\tilde{B}}^{\tilde{R}_6}(y) = \left\{min\left(\underline{f}^{\tilde{R}_6},\ \mu_T^{ID}(y)\right),\ min\left(\overline{f}^{\tilde{R}_6},\ \mu_T^{ID}(y)\right)\right\} \tag{3.33}$$

Here the outputs are two fuzzy type-2 sets; therefore, it cannot be written as a fixed value. Therefore, from here on, the process has been explained and final results have been calculated based on the MATLAB output.

3.5.4 Step 4: Aggregation of Rules Outputs

According to Eq.3.16, the aggregation is the union of all rule's outputs. Here, maximization is applied to all fuzzy outputs of rules as follows:

$$\mu_{\tilde{B}}(y) = \left\{\underline{\mu}_{\tilde{B}}(y),\ \overline{\mu}_{\tilde{B}}(y)\right\} = \left\{max\left(\underline{\mu}_{\tilde{B}}^{\tilde{R}_5}(y),\ \underline{\mu}_{\tilde{B}}^{\tilde{R}_6}(y)\right),\ max\left(\overline{\mu}_{\tilde{B}}^{\tilde{R}_5}(y),\ \overline{\mu}_{\tilde{B}}^{\tilde{R}_6}(y)\right)\right\} \quad (3.34)$$

where, $\mu_{\tilde{B}}(y)$ is the final type-2 fuzzy of $R1$ model.

3.5.5 Step 5: Type-reduction and Defuzzification of Fuzzy Output

In this step as the final step of the R1 model, first, we compute the centroid of the aggregated type-2 fuzzy set using the EKM algorithm to reduce type-2 to type-1 fuzzy set (type-reduction) then the defuzzification applied on the type-1 fuzzy set using the centroid method.

3.5.6 Further Process on Building Example Parameters Through $R2$ to $R8$ Models

For all other models from $R2$ to $R8$, the same steps calculated for $R1$ have been applied. According to Figure 3.9, the output of $R1$ for this building example is 0.5021, which is one of the inputs to $R3$. Then, in $R3$, it is fuzzified to the "Moderate" fuzzy set. The output of $R2$ is calculated by using two input variables, YC and CQ. For the above example, considering YC=1978 (which normalized to 0.5397 based on Section 3.3.2.6) and CQ=0.5, the output of the $R2$ model is obtained as 0.51. According to Figure 3.9, the output of the $R1$ and $R2$ models {0.5021, 0.51} are the inputs of the $R3$ model. At the fuzzification step for R3, these values are converted to fuzzy sets as {M, M}. The result of the $R3$ model based on these values is obtained as 0.5. The $R3$ output (0.5) and Structural System C3 (here we consider 0.9) are inputs of $R4$. The results of $R4$ based on these values is 0.88. The next model is $R5$, with inputs of soil type D (0.7) and seismic zone very high (0.95). The output of $R5$ based on these values is 0.8716. After obtaining the $R4$ and $R5$ outputs as {0.8841, 0.8716}, these values are inputs of $R6$. Considering calculated values, the output of $R6$ is 0.9473, which means the earthquake hazard safety of this building (I^{EHS}) is damage grade 5 or collapse. Compared to the actual damage of this building example, that is "Severe", the result shows a good approximation for this building; however, it is a bit overestimated, and is due to the safety factors considered through rules definitions. In the proposed model, two more fuzzy models are used as $R7$ for importance exposure and $R8$ for earthquake risk. The inputs of $R7$ in this example are assumed to be "Medium" for occupancy and "Medium" for usage. Therefore, the output of $R7$ in this example is 0.5, which is considered as "Medium" for building importance/exposure index (I^{IE}).

Finally, the inputs of the $R8$ model for this building come from the $R6$ and $R7$ outputs, which are {0.9473, 0.5}. Accordingly, the output of $R8$, which is the earthquake risk index (I^{ER}), is 0.623, which means a high risk for this building.

3.6 Implementation into Smartphone App: A Prototype

One aim of this thesis is to introduce a smartphone app prototype for earthquake hazard safety assessment of buildings based on the implementation of the proposed method to achieve an improved earthquake hazard safety assessment. The Earthquake Hazard Safety Assessment of buildings via smartphone App (EHSAPP) is expected to simplify and accelerate the assessment process, and to gather and process data online. The data contains coordinates of the building location to allow the use of building stock mapping and assess the potential hazard of the earthquake. The concept of this app has been introduced initially in [66] and validated by evaluating selected buildings in the case study presented in [68].

Figure 3.21 represents the life cycle of implementing and using the proposed method based on IT2FLS via android smartphones. It starts with the design concept where the set of goals, data science, and experts are required to decide what parameters are necessary to be considered and their rules and relationship to each other. Then, the proposed fuzzy model is implemented on the server. A data collection app (or web-based) is designed and programmed to work using the android smartphone system. As a result, the experts and trained engineers can perform building observation surveys and collect data in the field. The data transfer is on the server where the model is implemented, and the user (e.g., city authorities) can observe, monitor, and use the data in the inference stage. In this stage, the surveyor can also access the assessment results. Any further modification, feedbacks, or improvement to the model will be in the feedback stage.

Some screenshots of the EHSAPP have been shown in Figure 3.22. As can be seen, the user logs in to the app and then inputs the essential information and take a picture of the building. The GPS collects the geographical information, tags the location of the building, records the soil type, and inputs the seismic zone. Furthermore, the user enters the parameters required based on their observations, and consequently it computes and shows the I^{EHS}, I^{IE}, and I^{ER} of the building.

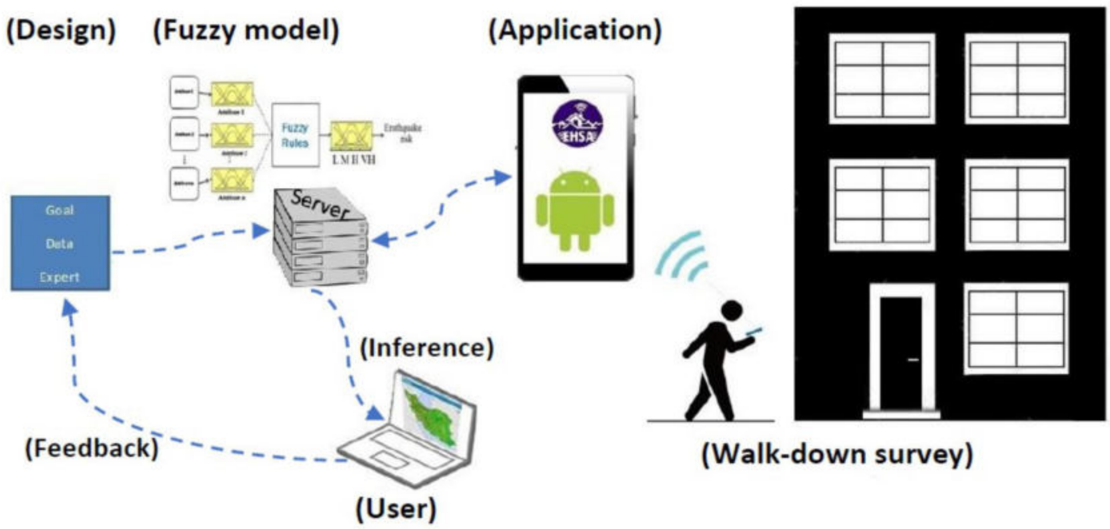


Figure 3.21: The life cycle of using the proposed method via the new Android app prototype on the smartphone

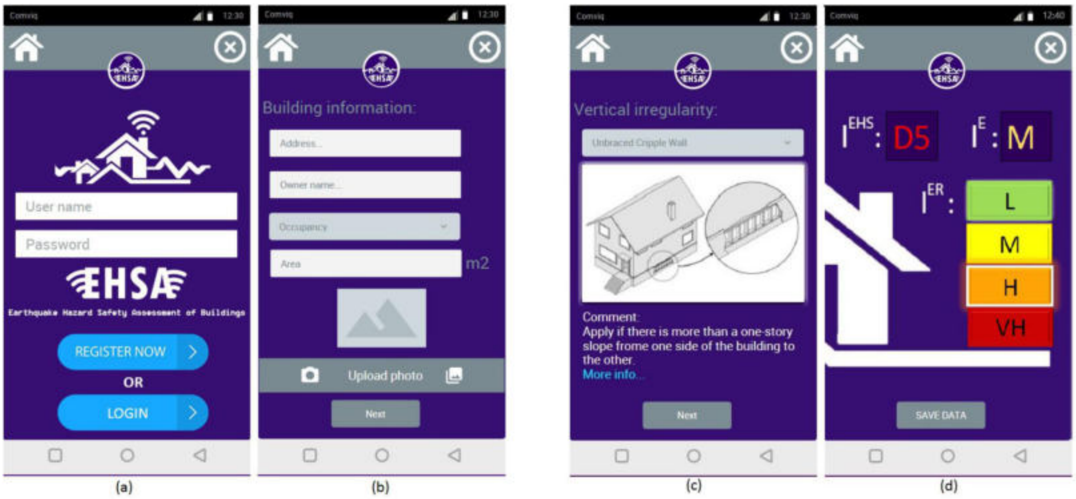


Figure 3.22: Screenshot of the proposed app: (a) first page, (b) building information, (c) entering buildings irregularities, (d) building earthquake hazard safety and risk assessment

Chapter 4

Results and Discussion

4.1 Introduction

As mentioned in the review of literature, despite the enhancements related to building construction, many regions still present a significant level of seismic risk as a consequence of the high vulnerability of the urban configuration of their cities. An improved method to assess the seismic vulnerability and safety of buildings and their risk level in urban areas is proposed in this contribution to advance the management of earthquake risk analysis and help in emergency scenarios. In this thesis, the methodology based on IT2FLS was implemented in MATLAB version 2019 (MATLAB is a registered trademark of The MathWorks, Inc.) using the provided fuzzy logic Toolbox. The implemented version of the IT2FLS toolbox in MATLAB allows the intuitive implementation of IT2FLSs, where it can cover all the phases of its design.

4.2 Case Study

The applicability of the proposed method is applied in two case studies and compared with some other available methods to identify and prioritize high-risk buildings and for guiding decisions on retrofitting or renewal. Data for this study were collected retrospectively from the archival material of the SERU (Structural Engineering Research Unit) database [173], which was collected from the street survey by a team of researchers from the Middle East Technical University (METU), Ankara, Turkey.

Turkey is located in a high seismicity region and has suffered significant losses due to several extreme earthquakes that have affected its various parts over the past two decades. While earthquakes are associated with damage and loss wherever they may occur, the destructive effects of those in Turkey are exacerbated by the large volume of code incompliant buildings constructed with inferior materials and quality. As a large scale remedial initiative, Turkey has recently embarked upon a grand challenge of retrofitting or renewing all high-risk buildings within the next 20 years [64]. Figure 4.1 shows the seismic hazard map of Turkey and the selected cities are highlighted.

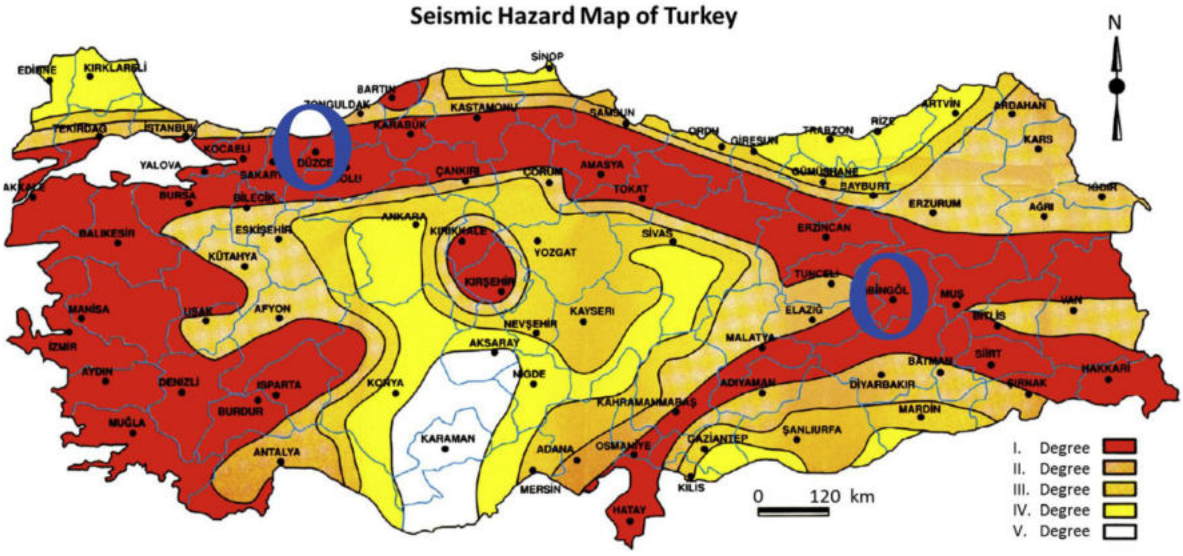


Figure 4.1: The seismic hazard map of Turkey and selected cities [5]

4.2.1 Bingöl Earthquake

The proposed method of this study has been examined by evaluating the buildings database of the Bingöl earthquake (May 1^{st}, 2003) in Turkey. For this purpose, the information of 28 buildings has been selected from the SERU database [173]. The Bingöl earthquake struck with a $M_w = 6.4$, reported PGA 535.3 cm/s^2, and PGV 36.1 cm/s [2] in the eastern part of Turkey. Moreover, a study by Akkar et al. [9] provides detailed technical information about the characteristics of the Bingöl earthquake. The damage state provided was given verbally, such as "collapse", "severe", "moderate", "light (low)", and "none", where more description on the detail of these levels can be found from [213].

A report from the observed damage to the buildings in different places in Bingöl stated that damages were mostly due to the properties of structures, and not due to the foundation conditions or any gross ground deformation [143]. Therefore, it has been assumed that, for assessing the vulnerability of the buildings in Bingöl, there are no corrections or additional parameters required for different soil conditions, and the soil condition of the selected area are quite uniform, predominantly granular alluvial deposits, which are dense to very dense (Soil Type C) [24] and the shear-wave velocity (V_s 30) in the upper 30 meters of soil in Bingöl was 529 m/s [2]. Bingöl falls under a high seismic zone with a 10 percent probability in 50 years with PGA of $0.4g$ from the seismic zoning map. All the necessary building information related to required parameters to perform RVS methodologies was collected from the data provided. For the entire vertical and plan irregularities, number "1" was admitted as "YES" and "0" was considered as "NO". For apparent building quality, "0", "1", and "2" were considered for "good", "moderate", and "poor", respectively. If the presence of any irregularity is not mentioned in the data provided, then it was considered as "NO". Also, the available data does not include sufficient information to compute building importance/exposure, thus no risk evaluation is provided.

The legend for damage levels is presented in Figure 4.2. Figures 4.3 to Figure 4.8 illustrate the performance modifiers and mapping over different damage states for selected RC buildings of Bingöl earthquakes in this study. From Figure 4.3 and 4.4, we can see that most of the buildings with plan irregularity and vertical irregularity have experienced more damage than without irregularities. Also, existence of vertical irregularity caused more damage than plan irregularity.

As can be seen from Figure 4.5, the Bingöl database had buildings within 2 to 5 stories, and most of the damages are for medium- to high-rise buildings. Figure 4.6 indicates that buildings with poor construction quality have experienced more damage than others. Similarly, in Figure 4.7, the buildings which were built before moderate code (earlier than 1998) received more damage than new buildings as the design standards and safety considerations developed; the legend of years related to construction is presented in the Table 4.1. From Figure 4.8, we can see that most of the observed RC buildings were built by C3 (moment-resisting frame) system. The legend related to the structural system is presented in the Table 4.2. As the number of buildings was limited, and for better understanding, the percentage shows the amount of distribution for each damage level and performance modifiers.

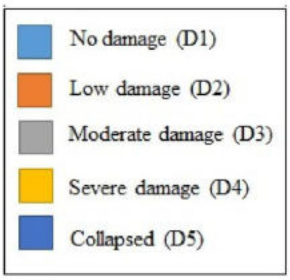


Figure 4.2: Legend for damage levels

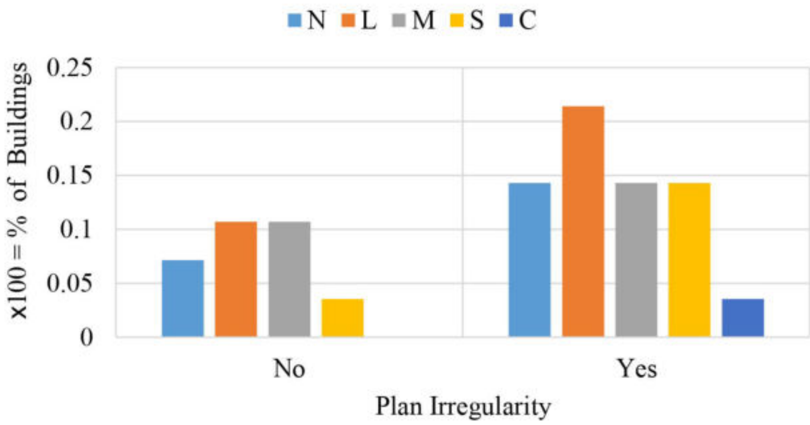


Figure 4.3: Mapping existence of plan irregularity over different damage states for RC buildings Bingöl earthquake

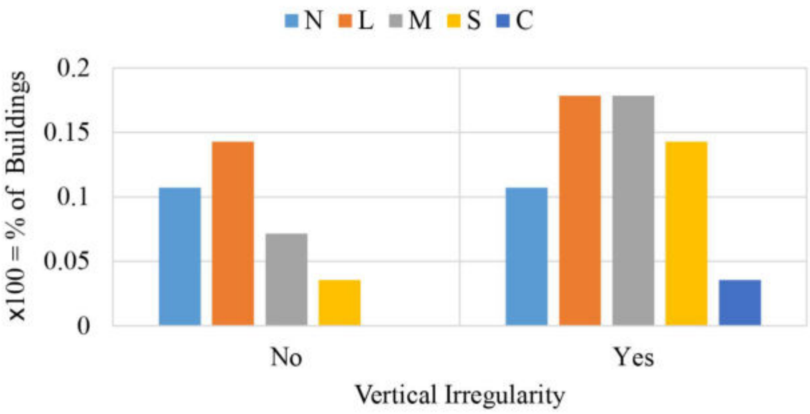


Figure 4.4: Mapping existence of vertical irregularity over different damage states for RC buildings Bingöl earthquake

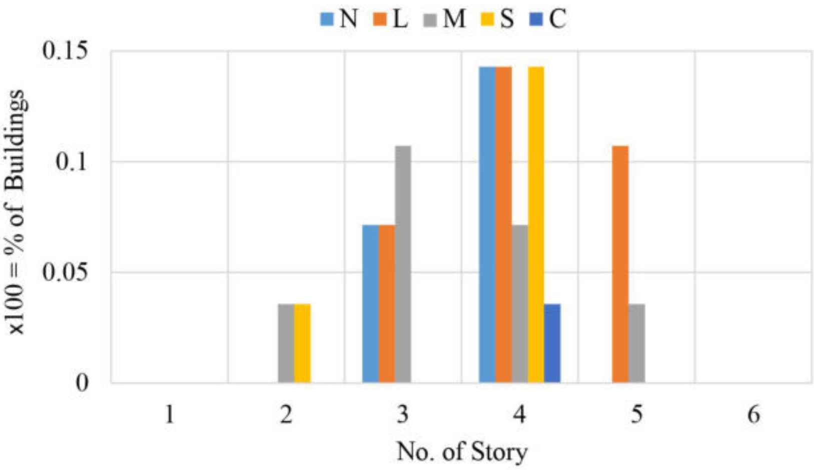


Figure 4.5: Mapping number of story over different damage states for RC buildings Bingöl earthquake

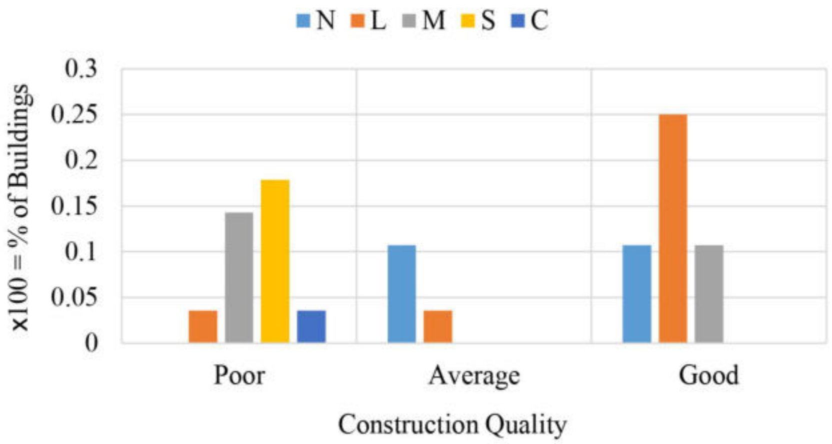


Figure 4.6: Mapping construction quality over different damage states for RC buildings Bingöl earthquake

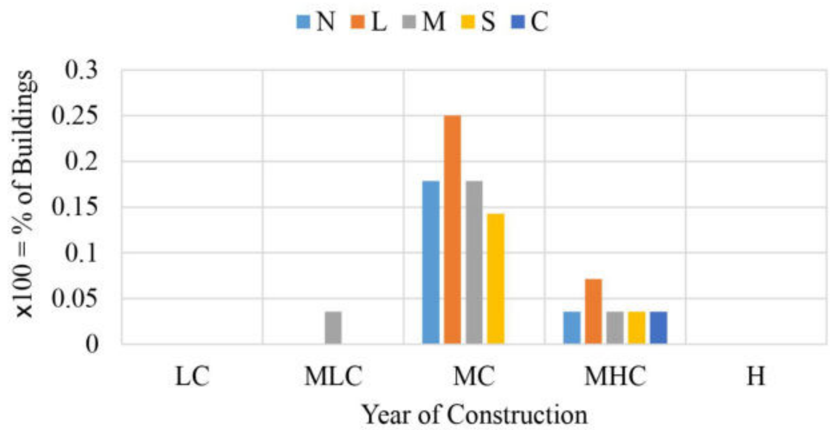


Figure 4.7: Mapping year of construction over different damage states for RC buildings Bingöl earthquake

Table 4.1: Legend for year of construction

LC	Low Code	YC≤1944
MLC	Moderate Low Code	1944<YC<1975
MC	Moderate Code	1975≤YC<1998
MHC	Moderate High Code	1998≤YC<2007
H	High Code	YC≥2007

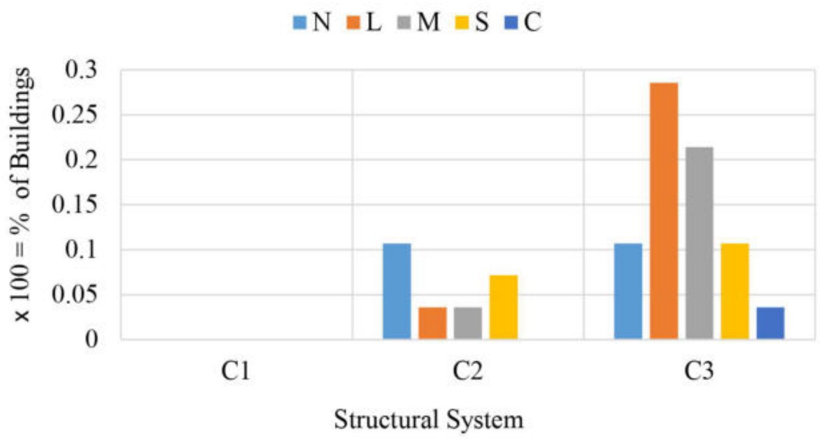


Figure 4.8: Mapping different structural systems over different damage states for RC buildings Bingöl earthquake

Table 4.2: Legend for structural system

C1	Concrete moment frames
C2	Concrete shear walls
C3	Concrete frames with infill masonry

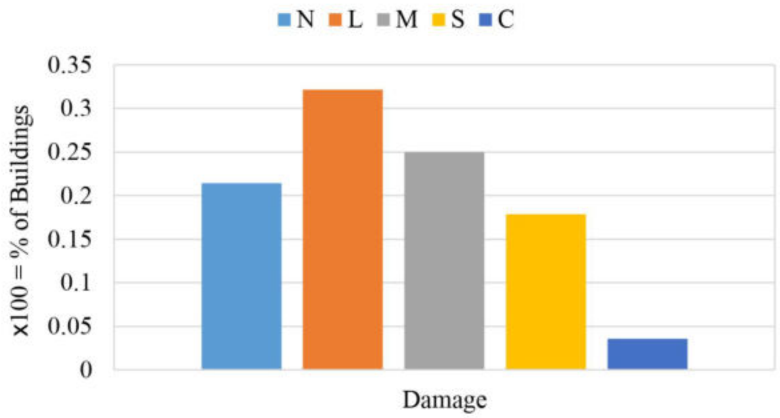


Figure 4.9: Damage state distribution of RC buildings in Bingöl earthquake

The distribution of observed damage to the buildings is presented in Figure 4.9. As can be seen, there is a Gaussian distribution skewed to the right which means that the foremost damage states were light (32%) to moderate (25%) while the collapsed buildings are at the lowest value (less than 5%).

Figure 4.10 shows the scatterplot matrix of variables of buildings collected from database. It is obvious from this figure that there is no linear relationship between the variables.

Descriptive statistics of variables from the RC building data from the Bingöl earthquake are presented in Table 4.3. As can be seen, the mean number of stories was approximately 4 stories;

more than half of the buildings had vertical and plan irregularity, respectively. In addition, it can be observed that most of the buildings had poor construction quality and averagely were built in 1993. The standard deviation of each parameter measures the dispersion of a dataset relative to its mean.

A Pearson's product-moment correlation was performed to assess the relationship between variables of buildings and observed damages and is illustrated in Table 4.4. Interestingly, there were small positive and negative correlations between variables of buildings to the damage as the Pearson correlation coefficients, r, is less than 0.3 [38]. However, there was not a statistically significant relationship between variables as most of the p-values were $p > 0.005$, which it can be concluded that all variables are linearly independent and may be used as input parameters of the proposed model.

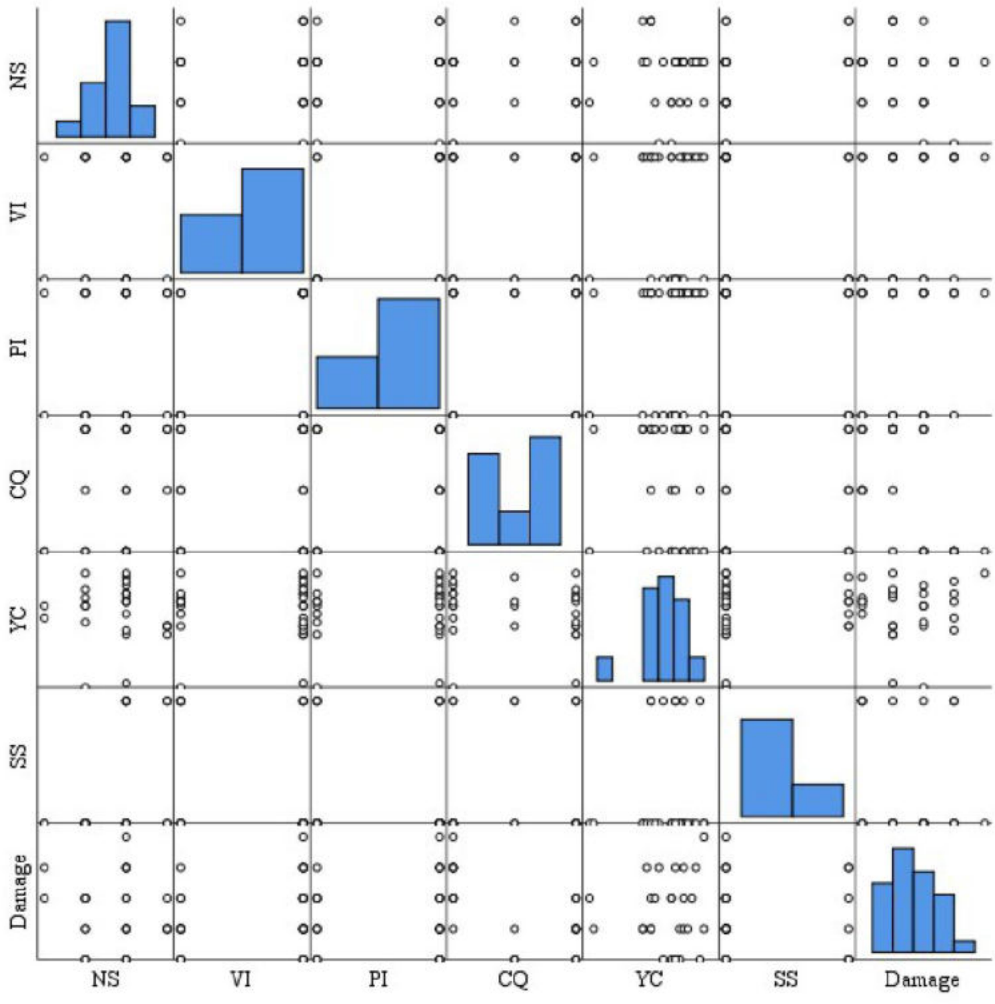


Figure 4.10: Scatterplot matrix of variables of RC buildings in Bingöl earthquake

Table 4.3: Mean and standard deviations of variables of RC buildings in Bingöl earthquake

Descriptive Statistics			
	Mean	Std. Deviation	N
NS	3.7500	0.79931	28
VI	0.6429	0.48795	28
PI	0.6786	0.47559	28
CQ	0.5357	0.47000	28
YC	1993.9643	6.83391	28
SS	0.1250	0.22048	28
Damage	2.5000	1.13855	28

Table 4.4: Pearson's correlation between variables of RC buildings in Bingöl earthquake

Correlations								
N = 28		NS	VI	PI	CQ	YC	SS	Damage
NS	Pearson Correlation	1	0.047	0.171	0.271	-0.090	.394*	-0.102
	Sig. (2-tailed)		0.810	0.386	0.163	0.649	0.038	0.606
VI	Pearson Correlation	0.047	1	.604**	0.058	0.007	-0.258	0.267
	Sig. (2-tailed)	0.810		0.001	0.771	0.971	0.185	0.170
PI	Pearson Correlation	0.171	.604**	1	-0.030	0.122	-0.132	0.103
	Sig. (2-tailed)	0.386	0.001		0.881	0.537	0.502	0.603
CQ	Pearson Correlation	0.271	0.058	-0.030	1	-0.138	0.045	-.623**
	Sig. (2-tailed)	0.163	0.771	0.881		0.484	0.821	0.000
YC	Pearson Correlation	-0.090	0.007	0.122	-0.138	1	0.089	0.050
	Sig. (2-tailed)	0.649	0.971	0.537	0.484		0.652	0.801
SS	Pearson Correlation	.394*	-0.258	-0.132	0.045	0.089	1	-0.111
	Sig. (2-tailed)	0.038	0.185	0.502	0.821	0.652		0.575
Damage	Pearson Correlation	-0.102	0.267	0.103	-.623**	0.050	-0.111	1
	Sig. (2-tailed)	0.606	0.170	0.603	0.000	0.801	0.575	
*. Correlation is significant at the 0.05 level (2-tailed).								
**. Correlation is significant at the 0.01 level (2-tailed).								

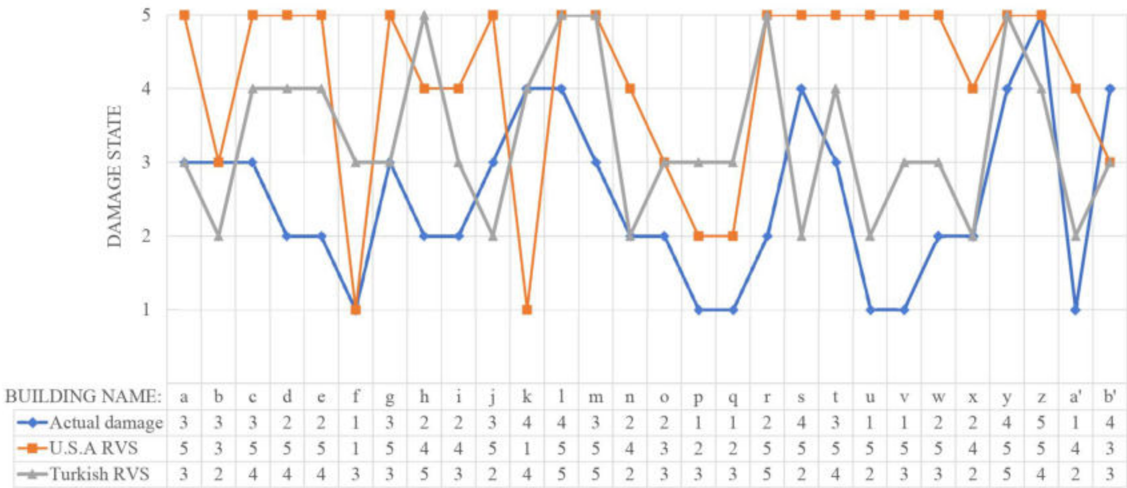


Figure 4.11: Damage state of selected building data from RVS methodologies method (adopted from [71])

Figure 4.11 presents the assessment of the building data set of Bingöl through different RVS methods in the study by Harirchian et al. [71]. To describe the performance of different RVS methods on the selected data for which the true values (actual damages) are known, a confusion matrix was used. Tables 4.5 to 4.8 display the confusion matrix of assessed buildings using U.S.A. RVS [195], Turkish RVS [14], Tesfamariam RVS [192, 191], and the proposed RVS, respectively. The result from the Tesfamariam RVS has been compared in this part due to the work on the same database of Bingöl. The accuracy from the confusion matrix is calculated as the total number of two correct predictions (True Positive + True Negative) divided by the total number of a dataset (Positive + Negative). From Tables 4.5 to 4.8, the accuracy is calculated as below:

- Accuracy of U.S.A. RVS: 3/28 = 0.107 or 10.7%
- Accuracy of Turkish RVS: 6/28 = 0.178 or 17.8%
- Accuracy of Tesfamariam RVS: 17/28 = 0.607 or 60.7%
- Accuracy of the proposed RVS: 18/28 = 0.643 or 64.3%

Table 4.5: Confusion matrix of assessed buildings in Bingöl earthquake by U.S.A. RVS

		Predicted label				
	n=28	D1	D2	D3	D4	D5
True label	D1	1	2	0	1	2
	D2	0	0	1	4	4
	D3	0	0	1	0	6
	D4	1	0	1	0	3
	D5	0	0	0	0	1

Table 4.6: Confusion matrix of assessed buildings in Bingöl earthquake by Turkish RVS

		Predicted label				
	n=28	D1	D2	D3	D4	D5
True label	D1	0	2	4	0	0
	D2	0	2	3	2	2
	D3	0	2	2	2	1
	D4	0	1	1	1	2
	D5	0	0	0	1	0

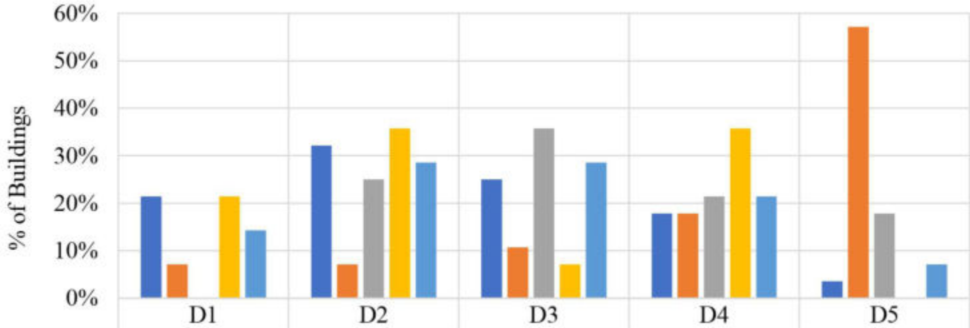
Table 4.7: Confusion matrix of assessed buildings in Bingöl earthquake by Tesfamariam RVS

		Predicted label				
	n=28	D1	D2	D3	D4	D5
True label	D1	4	2	0	0	0
	D2	2	6	0	1	0
	D3	0	2	2	3	0
	D4	0	0	0	5	0
	D5	0	0	0	1	0

Table 4.8: Confusion matrix of assessed buildings in Bingöl earthquake by proposed RVS

		Predicted label				
	n=28	D1	D2	D3	D4	D5
True label	D1	3	3	0	0	0
	D2	0	5	3	1	0
	D3	1	0	5	1	0
	D4	0	0	0	4	1
	D5	0	0	0	0	1

The results from the assessment of buildings by different RVS methods are illustrated in Figure 4.12. As can be seen in state D1, there were no buildings classified by Turkish RVS, and U.S.A. RVS evaluated only one-third of the actual damage state. In group D2, 32% of buildings were included, U.S.A. RVS presented inadequate assessment level by having 7% while proposed RVS and Turkish RVS classified 32% and 25%, respectively. Moreover, Tesfamariam RVS in the D2 group had a tiny overestimation but, in contrast, showed a massive underestimate in state D3. The Turkish and proposed RVS presented a small overvaluation in state D3, where the U.S.A. RVS classified less than half of the actual damage in this group. Most of the RVS methods had an excellent performance in state D4 evaluation, but the Tesfamariam RVS had an assessment twice as large as the actual damage. Finally, 4% of buildings belong to state D5, where the U.S.A. RVS assessed approximately 57% of buildings in this damage group, and the Tesfamariam RVS did not classify buildings in this group. Overall, from the graph, it can be concluded that the overestimation from U.S.A. and Turkish RVS methods is too high, which is not realistic and does not make sense from the economic and sustainability points of view. The Tesfamariam RVS, in general, presented a better evaluation in comparison to the U.S.A. and Turkish methods, but it did not show a proper distribution and, in some points, had conflicting results. Therefore, the proposed RVS presented a high-quality evaluation, where it includes all damage groups, and due to the fact of the considered factor of safety, it has evaluated more buildings as being in one category higher than the actual damage. In a study on the same data of Bingöl and using different MCDM methods [67], the best-achieved accuracy was 35% which, shows that the proposed method in this study has significant improvement.



	D1	D2	D3	D4	D5
Actual damage	21%	32%	25%	18%	4%
U.S.A. RVS	7%	7%	11%	18%	57%
Turkish RVS	0%	25%	36%	21%	18%
Tesfamariam RVS	21%	36%	7%	36%	0%
Proposed RVS	14%	29%	29%	21%	7%

Figure 4.12: Distribution of damage grade of buildings in Bingöl earthquake assessed by different RVS

4.2.2 Düzce Earthquake

On November 12^{th}, 1999, a powerful $M_W = 7.1$ earthquake struck the city of Düzce (Turkey) within a PGA approximately $0.821g$ and PGV of 66.9 m/s [24]. A district in Düzce with a total number of 484 three- to six-story RC buildings was surveyed and collected by SERU [173] after the Düzce earthquake. Moreover, soil conditions were uniform, consisting of stiff clays with interbedded layers of dense sands and gravels. The measured (V_s 30) at DZC station was 294 m/s, which categorized the soil as a ground type D according to classification in this study, and the topography was flat over the surveyed district [36]. Düzce is located in a high seismic zone and the information extracted from the database was similar to Bingöl.

The legend for damage levels is presented in Figure 4.2. Figures 4.13 to 4.18, illustrate the performance modifiers and mapping over different damage states for selected RC buildings of Düzce earthquakes in this study. The observation in Düzce shows that the buildings with a lower number of stories have sustained less damage than buildings with a larger number of stories [186].

From Figures 4.13 and 4.14, we can see that most of the buildings with plan irregularity and vertical irregularity have experienced more damage than without irregularities. Also, the existence of vertical irregularity caused more damage than plan irregularity. According to this observation and the observations from Bingöl it can be concluded that existence of vertical irregularity causes more damages to the buildings. As can be seen from Figure 4.15, the Düzce database had buildings within 2 to 6 stories, and most of the severe and collapse damages were for 4 to 6 story buildings.

Figure 4.16 indicates that buildings with average construction quality have experienced more damage than others. However, in Figure 4.17, the buildings which were built before moderate code (before 1998) were damaged more than new buildings as the design standards and safety considerations developed. It can be concluded that the design code in Turkey has been significantly improved after 1998.

From Figure 4.18, we can see that most of the observed RC buildings were built using the C3 (concrete frames with infill masonry) system, followed by C2. From the observation of the structural system, it can also be concluded that typical RC buildings in Turkey are designed using C3 and C2 systems. Legends related to the year of construction and structural system have been illustrated in Tables 4.1 and 4.2, respectively.

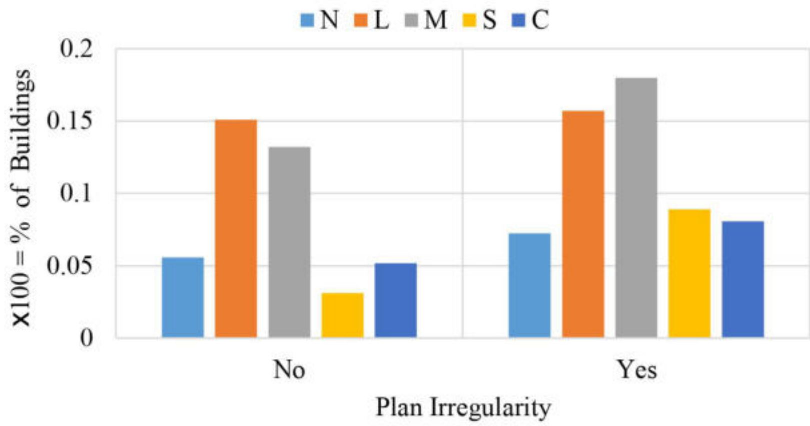


Figure 4.13: Mapping existence of plan irregularity over different damage states for RC buildings Düzce earthquake

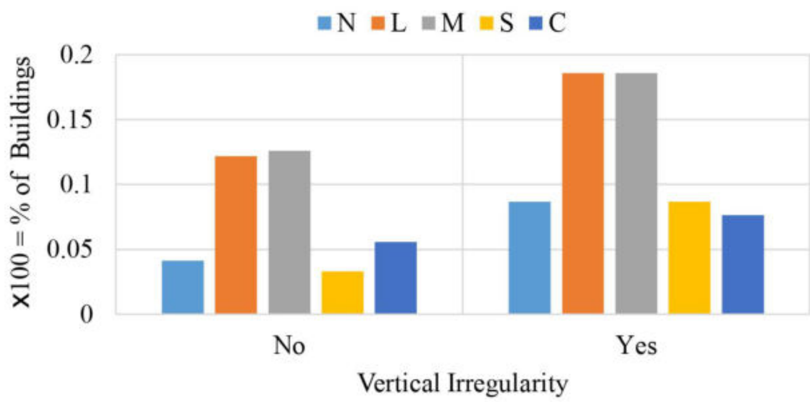


Figure 4.14: Mapping existence of vertical irregularity over different damage states for RC buildings Düzce earthquake

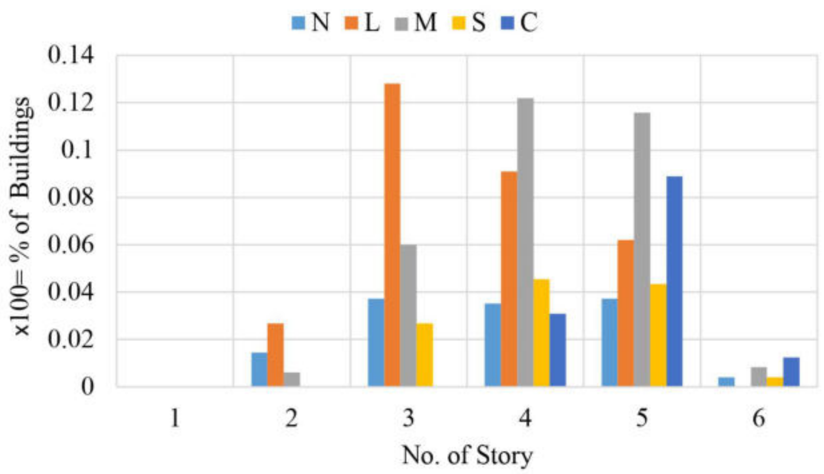


Figure 4.15: Mapping number of story over different damage states for RC buildings Düzce earthquake

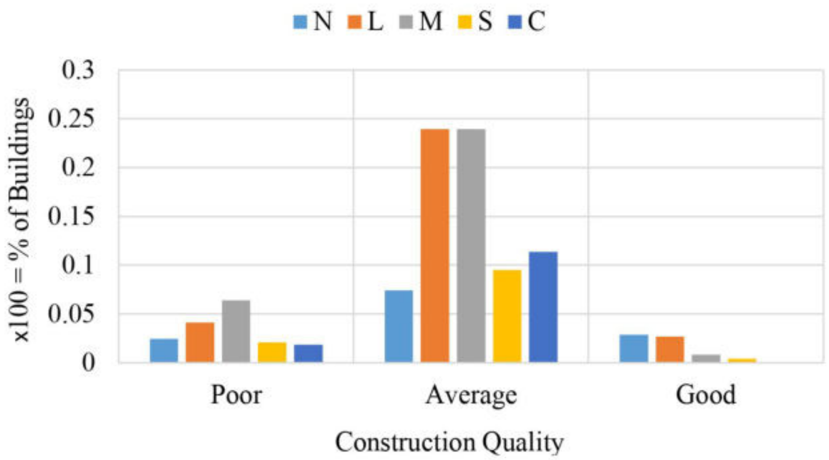


Figure 4.16: Mapping construction quality over different damage states for RC buildings Düzce earthquake

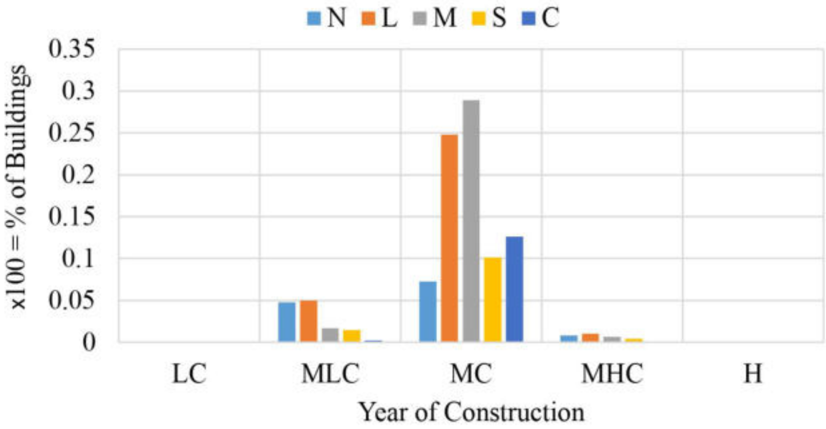


Figure 4.17: Mapping year of construction over different damage states for RC buildings Düzce earthquake

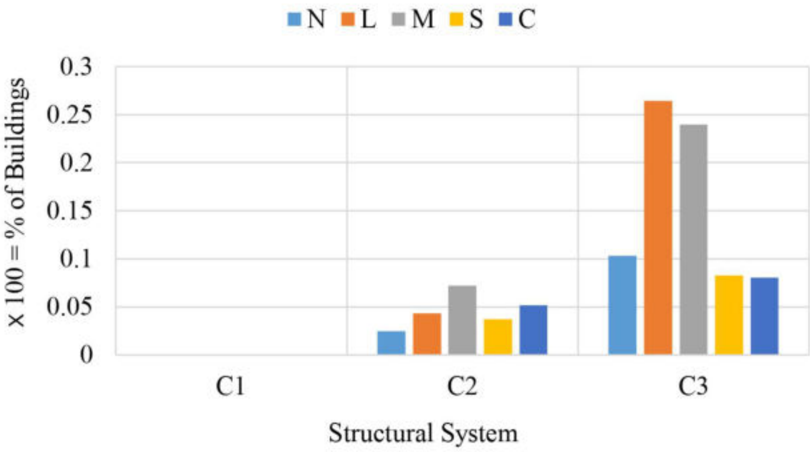


Figure 4.18: Mapping different structural systems over different damage states for RC buildings Düzce earthquake

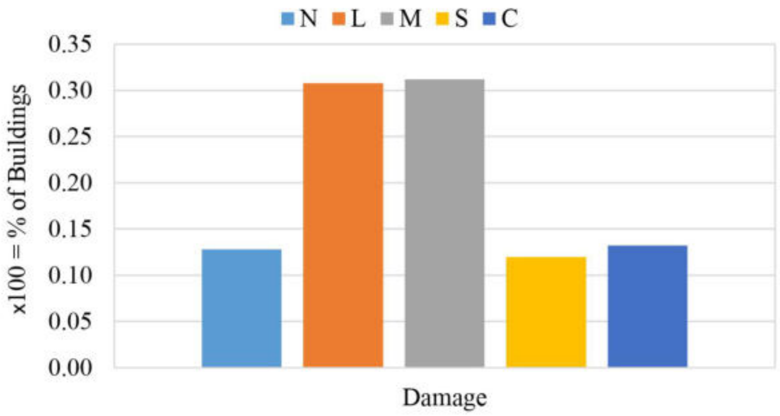


Figure 4.19: Damage state distribution of RC buildings in Düzce earthquake

Figure 4.19 presents the distribution of observed damage to the buildings where about 31% of the damage states were light and moderate equally. the distribution of other damage states were also close to each other and include less than 15% of buildings for each state.

Figure 4.20 shows the scatterplot matrix of variables of buildings collected from the database. It is clear from this figure that there is no linear correlation between the variables and they are uncorrelated or if there is any, it is very small.

Table 4.9 presents the descriptive statistics of variables from RC building data from the Düzce earthquake. From the table, we can see that the mean number of stories was approximately 4, more than half of the buildings were with vertical and plan irregularity, respectively. It can be observed that most of the buildings had moderate construction quality and were built on average in 1986.

A Pearson's product-moment correlation was run to assess the relationship between variables of buildings and observed damages and is illustrated in Table 4.10. As can be seen there were small positive and negative correlations between variables of buildings to the damage as, Pearson correlation coefficients of them, r, is less than 0.3 [38] and in some cases there were medium positive and negative correlations, e.g., number of stories to year of construction, where r is greater than 3. However, there was not a statistically significant relationship between variables because the two-tailed significance value (p-value) of the correlation coefficient was mainly $p > 0.005$. Thus, it can be concluded that all variables can be independent linearly and can be used as input parameters of the proposed model.

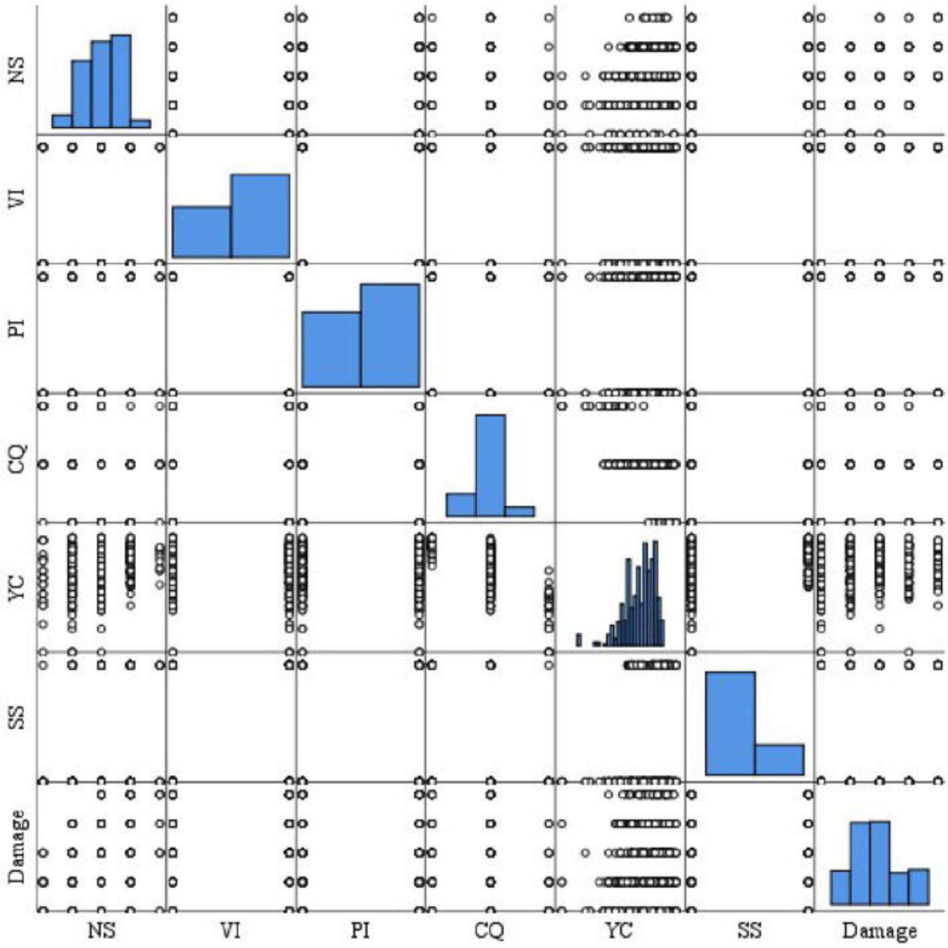


Figure 4.20: Scatterplot matrix of variables of RC buildings in Düzce earthquake

Table 4.9: Mean and standard deviations of variables of RC buildings in Düzce earthquake

Descriptive Statistics			
	Mean	Std. Deviation	N
NS	4.0579	0.95051	484
VI	0.6219	0.48541	484
PI	0.5785	0.49431	484
CQ	0.4494	0.23865	484
YC	1986.2934	9.09535	484
SS	0.1147	0.21042	484
Damage	2.8202	1.19986	484

Table 4.10: Pearson's correlation between variables of RC buildings in Düzce earthquake

Correlations								
N = 484		NS	VI	PI	CQ	YC	SS	Damage
NS	Pearson Correlation	1	.187**	.114*	-.215**	.326**	.272**	.372**
	Sig. (2-tailed)		0.000	0.012	0.000	0.000	0.000	0.000
VI	Pearson Correlation	.187**	1	.215**	-0.005	-0.044	0.050	-0.014
	Sig. (2-tailed)	0.000		0.000	0.918	0.337	0.269	0.761
PI	Pearson Correlation	.114*	.215**	1	-0.085	.133**	.127**	0.088
	Sig. (2-tailed)	0.012	0.000		0.063	0.003	0.005	0.052
CQ	Pearson Correlation	-.215**	-0.005	-0.085	1	-.659**	-.193**	-.115*
	Sig. (2-tailed)	0.000	0.918	0.063		0.000	0.000	0.011
YC	Pearson Correlation	.326**	-0.044	.133**	-.659**	1	.275**	.218**
	Sig. (2-tailed)	0.000	0.337	0.003	0.000		0.000	0.000
SS	Pearson Correlation	.272**	0.050	.127**	-.193**	.275**	1	.176**
	Sig. (2-tailed)	0.000	0.269	0.005	0.000	0.000		0.000
Damage	Pearson Correlation	.372**	-0.014	0.088	-.115*	.218**	.176**	1
	Sig. (2-tailed)	0.000	0.761	0.052	0.011	0.000	0.000	
**. Correlation is significant at the 0.01 level (2-tailed).								
*. Correlation is significant at the 0.05 level (2-tailed).								

Tables 4.11 to 4.13 display the confusion matrix of assessed buildings by the U.S.A., Turkish, and proposed RVS, respectively. From these tables, the accuracy will be calculated as below:

- Accuracy of U.S.A. RVS: $83/484 = 0.171$ or 17.1%
- Accuracy of Turkish RVS: $137/484 = 0.283$ or 28.3%
- Accuracy of the proposed RVS: $301/484 = 0.622$ or 62.2%

It should be noted that, in studies conducted by Harirchian et al. [73, 72] and also Tesfamariam and Liu [190] on the similar data by application of machine learning techniques, the accuracy rate was approximately 52% and 46%, respectively.

Table 4.11: Confusion matrix of assessed buildings in Düzce earthquake by U.S.A. RVS

		Predicted label				
	n=484	D1	D2	D3	D4	D5
True label	D1	1	2	15	4	40
	D2	1	5	37	20	86
	D3	0	4	36	23	88
	D4	0	2	8	6	42
	D5	0	0	13	16	35

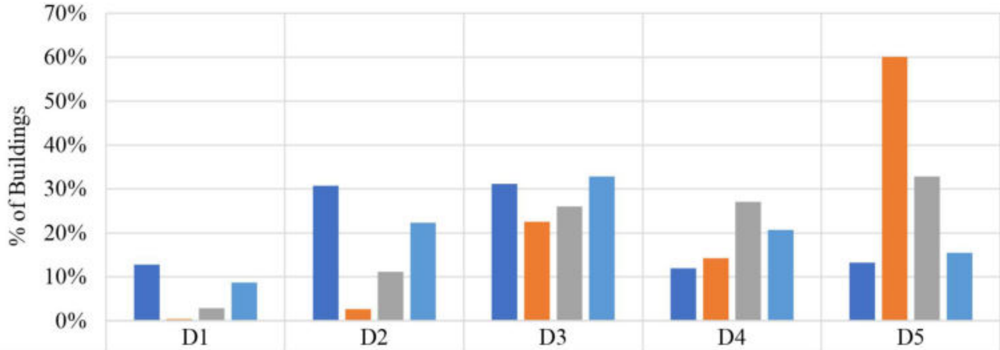
Table 4.12: Confusion matrix of assessed buildings in Düzce earthquake by Turkish RVS

		Predicted label				
	n=484	D1	D2	D3	D4	D5
True label	D1	10	15	17	12	8
	D2	4	32	52	36	25
	D3	0	6	43	38	64
	D4	0	1	11	18	28
	D5	0	0	3	27	34

Table 4.13: Confusion matrix of assessed buildings in Düzce earthquake by the proposed RVS

		Predicted label				
	n=484	D1	D2	D3	D4	D5
True label	D1	32	19	11	0	0
	D2	10	84	38	17	0
	D3	0	5	102	35	9
	D4	0	0	7	34	17
	D5	0	0	1	14	49

The results from the assessment of buildings by different RVS methods are presented in Figure 4.21. As can be seen in state D1, there were no buildings classified by the U.S.A. RVS, Turkish RVS evaluated only one-fourth of the actual damage state, and the proposed RVS evaluated 9% out of 13%. In group D2, 31% of buildings were included, and the U.S.A. RVS presented an inadequate assessment level of 3% while the Turkish RVS and the proposed RVS classified 11% and 22%, respectively. Turkish RVS and the proposed RVS presented a good assessment (26% and 33%) in state D3 where the U.S.A. RVS classified less than the actual damage in this group (23%). U.S.A. RVS had an excellent performance in state D4 evaluation, but other methods had an assessment twice as large as the actual damage. Lastly, 13% of buildings belong to state D5, where the U.S.A. and Turkish RVS assessed approximately 60% and 33% of buildings in this damage group, respectively, and the proposed RVS presented a good agreement with the actual damage in this state. In general, from the graph, it can be concluded that the overestimation of the U.S.A. and Turkish RVS is too high, which is not realistic and does not make sense from the economic and sustainability points of view. The proposed RVS presented a proper evaluation where it includes all damage groups, and, due to the fact of the considered factor of safety in the rules, it has evaluated more buildings as being in one category higher than the actual damage from state D3 and above. Moreover, the nature of the database could lead to achieving these assessments, which could be improved by using good quality data and more databases.



	D1	D2	D3	D4	D5
Actual damage	13%	31%	31%	12%	13%
U.S.A. RVS	0%	3%	23%	14%	60%
Turkish RVS	3%	11%	26%	27%	33%
Proposed RVS	9%	22%	33%	21%	15%

Figure 4.21: Distribution of damage grade of buildings in Düzce earthquake assessed by different RVS

4.3 Summary

The robustness of the proposed method was confirmed after 512 different buildings from two different cities were examined as case studies. These buildings were affected by earthquakes. It was proved that the assessed vulnerability classes were very close to the actual damage levels observed in the buildings, which, in comparison to previous methods, provided a more reliable distribution between different damage levels.

The proposed method is more accurate than other methods where this rate shows a significant improvement of about 30 to 40% compared to common national methods and approximately 12 to 16% in comparison with machine learning methods. This achievement, in addition to financial benefits and better natural disaster management planning, also makes building retrofitting more intelligent and saves the lives of its residents.

It must be mentioned that it is not expected from RVS methods to have high accuracy and an exact estimate of the possible damage. In reality, an overwhelming number of many factors and effective parameters play roles in the vulnerability of a building. The main aim of the RVS method is to obtain acceptable classification and initial assessment of damage and be prepared to prevent catastrophe. Also, an initial assessment of the risk level leads to the provision of emergency and rescue services. Benefits such as proper budget allocation and prioritization of building retrofitting and providing measures to prevent damage to buildings and its occupants are among the benefits of this method.

Chapter 5

Conclusion

The final chapter of the thesis is dedicated to the summary of the study's achievements. RVS methods should be implemented to determine the seismic risk state of large building stocks, as detailed analysis methods are not suitable for analyzing a large number of buildings due to the requirements at the analysis stage. In addition, the number of skilled staff required to perform detailed seismic assessment is too high to be practical.

Many factors, such as older design codes and poor practices at the time of design and construction, contribute to the vulnerability of existing RC buildings. In order to minimize seismic damage and improve safety, older buildings, many of which are still in use, need to be assessed further and strengthened. RVS can be used during this process for the detection of highly vulnerable buildings. This thesis uses a risk-based prioritization process, which incorporates damage potential as well as building failure consequences. The prioritization considers seismic site condition, building vulnerability and importance, and the exposure of the occupants to the hazard.

Hierarchical structures are used along with the knowledge and experience of practitioners are combined in the proposed method. Using two-stage hierarchical structure modeling created from assessments and subdivisions of buildings in terms of hazard safety and importance/exposure, the earthquake risk level is achieved. The earthquake hazard safety evaluations occur in the first stage, including the FEMA 154 parameters: soil type, seismic zone, number of stories, building type, vertical irregularity, plan irregularity, year of construction, and construction quality. The importance/exposure of buildings along with parameters such as building use, occupancy, and time of the event are considered in the second stage for the purpose of post-earthquake planning and management. A walk-down survey, site visit, interview with the owner, and engineering drawings can be used to obtain these parameters with relative ease.

Although, the walk-down survey is subject to vagueness and uncertainty and is modeled through the type-2 fuzzy set theory to overcome this problem. In addition, the fuzzy modeling approach is utilized to incorporate intuitive engineering expertise in the model. The proposed method is validated using the 1999 Düzce Earthquake data, and 2003 Bingöl Earthquake data in Turkey. The fuzzy rule-based modeling and heuristic building vulnerability modules are implemented in a prototype smartphone app. It helps to provide a user friendly, simple, and accessible method to evaluate the safety level of buildings and prioritize buildings for further retrofitting.

5.1 Highlights

This work confirmed the usefulness of risk-based prioritization of RC buildings in seismically active areas. A fuzzy-based evaluation method is proposed, and a prototype of a smartphone app is offered for faster, easier, and more accurate evaluation. Therefore, the following individual points can be concluded:

- According to the review of the current state, the proposed method and smartphone application is a novel application of IT2FLS in RVS, and despite the limitations, these are valuable achievements in light of new RVS and earthquake risk evaluation of buildings,
- The risk analysis of existing buildings is of the utmost importance for the management and reduction of earthquake risk,
- The hierarchical structure of earthquake risk analysis is a simple, explainable, and knowledgeable method for the prioritization of RC buildings, moreover caused a significant reduction in the number of rules, instead of 162,000 rules, only 141 rules were defined in this study,
- Data for the assessment of stage 1 and 2 can easily be obtained from an observation survey and does not require much time and on-site experimental testing; however, this model provides four different indices that can be used for various purposes,
- Any uncertainty involved in the subjective assessment of RC buildings is covered through the type-2 fuzzy set theory,
- Stage 1 evaluation is developed by considering building vulnerability parameters as provided in FEMA 154 screening guideline, and validation performed through the 2003 Bingöl earthquake and 1999 Düzce earthquake damage database shows good correlation, albeit extracted from limited data sets.

5.2 Future Recommendations

Future investigations are necessary to validate the types of conclusions that can be drawn from this study. A number of recommendations for future research are given below:

- Developing and programming the proposed prototype of the smartphone app and make it able to be accessed by different authorities and monitored on a server,
- Using more building damage databases to optimize the proposed method and be coupled with analytical work,
- Recognizing the effect of parameters in more detail, especially in types of irregularities and other types of structures,
- Considering the effect of different soil types, liquefaction and landslide hazard in addition ground motion,
- Investigating more on the building importance/exposure module and relevant parameters,
- Integrating a geographical information system (GIS) to the proposed method and smartphone app for improving building stock monitoring.

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Appendix

TÜBİTAK - METU

Structural Engineering Research Unit

Middle East Technical University, Civil Engineering Department, 06531, Ankar

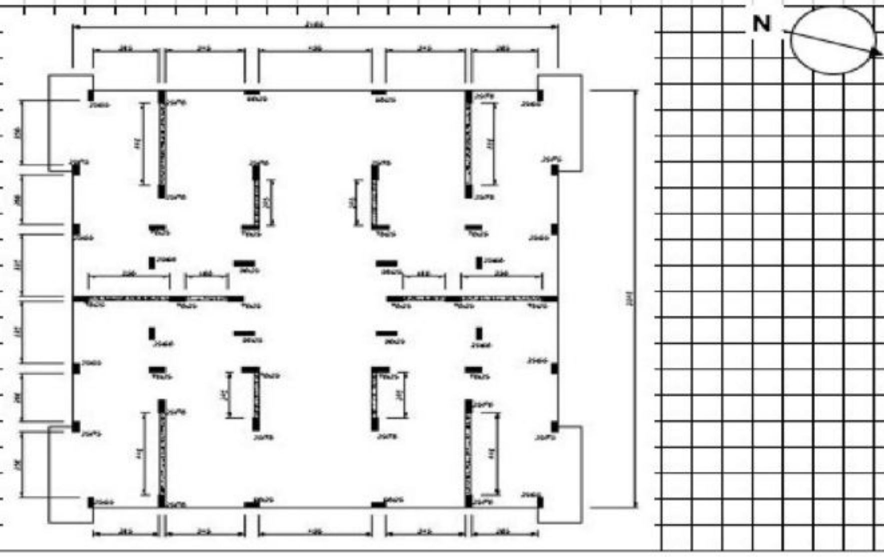
Tel: (312)210 24 51, Fax: (312) 210 11 93

IÇTAG I574

VELOPMENT OF SEISMIC VULNERABILITY ASSESSMENT METHODOLOG

1. GENERAL DATA

Building No	: BNG-3-4-1		Date of Survey :	08 / 05 / 2003
Building Adress	: Belediye Kooperatifleri-Aydınlar Yapı Koop. A Blok			
Building Coordinates	: E 629685	N 4306400	Photo No :	973-977
Construction Date	: / / 1998			
Damage State	: Structural-LIGHT Infill-NONE			
Survey Team	: Aydogan, Bayılı, Erdem, Yalım			



y

x

Plan View

2. BUILDING INFORMATION

Floor	Number	Story Height (m)	Story Area (m²)	Explanation			
Basement	1		472,58				
Ground	1	2,80	488,58				
Mezzanine							
Normal	3	2,80	488,58				
Penthouse							
Are additional stories exist?				Yes		No	X

1

Figure 1: Sheet 1 of available form of data for one building in Bingöl [173]

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Position	Independent	X	Dependent from one side		Dependent from two sides	
	Is the building on inclined surface?		Yes		No	X
Dilatation with neighbours	Yes		No		Undetermined	
Story level with neighbours	Same				Different	

Irregularities			
		Yes	No
Irregularities in Plan			
A1 :	Torsional Irregularity		X
A2 :	Floor Irregularity		X
A3 :	Discontinuity in Plan		X
A4 :	Nonparallel Axes of Structural Elements		X
Irregularities in Elevation			
B1 :	Strength Irregularity (Weak Story)		X
B2 :	Stiffness Irregularity (Soft Story)		X
B3 :	Discontinuity of Vertical Structural Elements :		X
Number of continuous frames in each direction	X-direction 5	Y-direction	4

3. STRUCTURAL SYSTEM PROPERTIES

Structural System Type	Reinforced Concrete Frame	X
	Reinforced Concrete Frame+Shear Wall	

Material of Infill Wall	Hollow brick	X
	Solid Brick	
	Concrete briquet	
	Ytong brick	
	Other (explain):	

Material of Shear Wall at Basement	Stone	
	R/C wall	X
	Solid brick	
	Concrete briquet	
	Other (explain):	

Floor System	Flat slab with beams	X
	Infilled joist slab	
	Unfilled joist slab	
	Flat slab without beams	
	Other (explain):	

2

Figure 2: Sheet 2 of available form of data for one building in Bingöl [173]

TÜBİTAK - METU

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Material Summary

Hammer Test								
No	**Specimen**	**Hammer Reading**						
	Column outside	18,0	**Strength,fck :**					**Mpa**
	Column outside	24,8	**Modulus of Elasticity, Ec :**					**Gpa**
	Column inside	22,1	**Reinforcement Class**					
			S220 (St I)	X	**S420 (St III)**		**S500 (St IV)**	
			Reinforcement Type					
			Plain	X	**Deformed**			

4. SYSTEM, WORKMANSHIP and GENERAL QUALITY EVALUATION

Evaluation Topic		**Explanations**	**Point 0=bad 5=good**
Present quality of building			
Material Qualities	Concrete		1
	Reinforcement		1
	Infill Wall		2
System Weaknesses	Short Column		5
	Soft Story		5
	Weak Story		
Are there any problems in the connections of beam-column joints?			2
Are there at least two bays in each direction?			5
Is there a possibility of pounding?			5
Are architectural systems of stories similar?			5
Are infill walls continuous?			5
Does corrosion problem exist in structure?			
Are there any discontinuity in vertical members			
Is lateral resisting system adequate?			

Additional Notes

3

Figure 3: Sheet 3 of available form of data for one building in Bingöl [173]

Table 1: Vertical irregularities according to FEMA P-154[55]

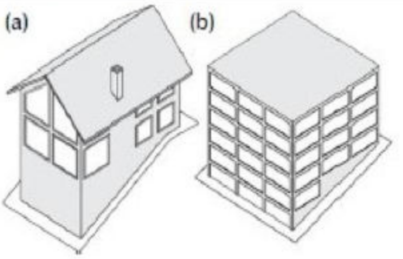
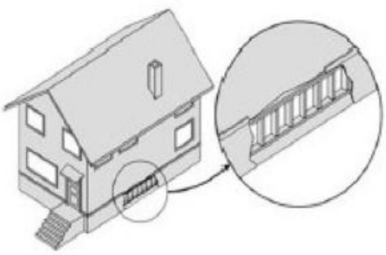
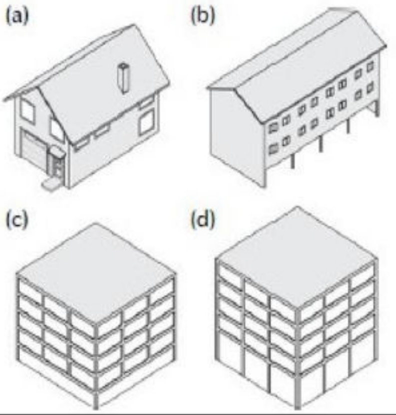
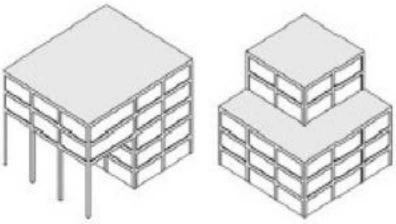
Vertical Irregularity		Severity	Level 1 Instructions
Sloping Site	(a) (b) 	Varies	Apply if there is more than a one-story slope from one side of the building to the other. Evaluate as Severe for W1 buildings as shown in Figure (a); evaluate as Moderate for all other building types as shown in Figure (b).
Unbraced Cripple Wall		Moderate	Apply if unbraced cripple walls are observed in the crawlspace of the building. This applies to W1 buildings. If the basement is occupied, consider this condition as a soft story.
Weak and/or Soft Story	(a) (b) (c) (d) 	Severe	Apply: Figure (a): For a W1 house with occupied space over a garage with limited or short wall lengths on both sides of the garage opening. Figure (b): For a W1A building with an open front at the ground story (such as for parking). Figure (c): When one of the stories has less wall or fewer columns than the others (usually the bottom story). Figure (d): When one of the stories is taller than the others (usually the bottom story).
Out-of-Plane Setback		Severe	Apply if the walls of the building do not stack vertically in plan. This irregularity is most severe when the vertical elements of the lateral system at the upper levels are outboard of those at the lower levels as shown in Figure (a). The condition in Figure (b) also triggers this irregularity. If nonstacking walls are known to be nonstructural, this irregularity does not apply. Apply the setback if greater than or equal to 2 feet.

Table 2: Vertical irregularities according to FEMA P-154[55]

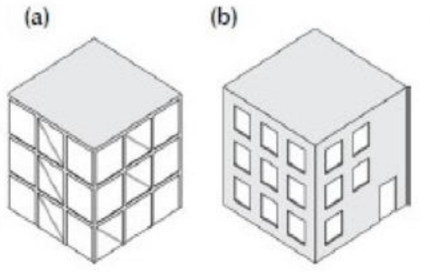
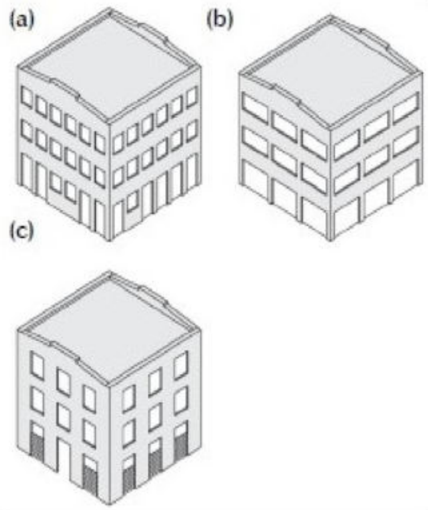
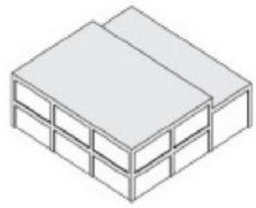
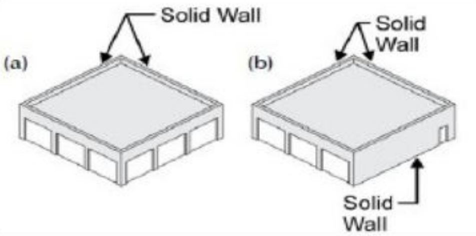
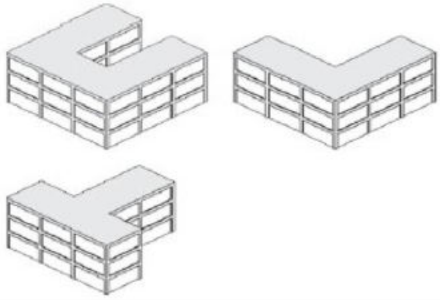
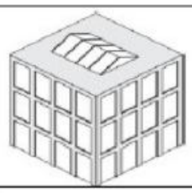
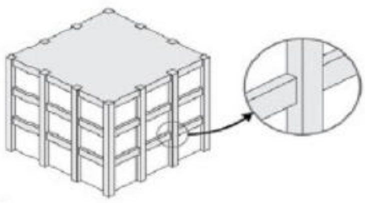
In-plane Setback		Moderate	Apply if there is an in-plane offset of the lateral system. Usually, this is observable in braced frame (Figure (a)) and shear wall buildings (Figure (b)).
Short Column/Pier		Severe	Apply if: Figure (a): Some columns/piers are much shorter than the typical columns/piers in the same line. Figure (b): The columns/piers are narrow compared to the depth of the beams. Figure (c): There are infill walls that shorten the clear height of the column. Note this deficiency is typically seen in older concrete and steel building types.
Split Levels		Moderate	Apply if the floors of the building do not align or if there is a step in the roof level.

Table 3: Plan irregularities according to FEMA P-154[55]

Plan Irregularity		Level 1 Instructions
Torsion		Apply if there is good lateral resistance in one direction, but not the other, or if there is eccentric stiffness in plan (as shown in Figures (a) and (b); solid walls on two or three sides with walls with lots of openings on the remaining sides).
Non-Parallel Systems		Apply if the sides of the building do not form 90-degree angles.
Reentrant Corner		Apply if there is a reentrant corner, i.e., the building is L, U, T, or + shaped, with projections of more than 20 feet. Where possible, check to see if there are seismic separations where the wings meet. If so, evaluate for pounding.
Diaphragm Openings		Apply if there is a opening that has a width of over 50% of the width of the diaphragm at any level.
Beams do not align with columns		Apply if the exterior beams do not align with the columns in plan. Typically, this applies to concrete buildings, where the perimeter columns are outboard of the perimeter beams.