DAMAGE DISTRIBUTION AND BEHAVIOUR OF BUILDINGS IN BHUJ EARTHQUAKE -2001

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF
MASTER OF TECHNOLOGY
IN
STRUCTURAL ENGINEERING

Submitted by:

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(2K21/STE/18)

Under the supervision of
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and
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CANDIDATE'S DECLARATION

I, Raina Venposh, 2K21/STE/18, student of M.Tech Structural Engineering, hereby declare that the project Dissertation titled "DAMAGE DISTRIBUTION AND BEHAVIOUR OF BUILDINGS IN BHUJ EARTHQUAKE-2001" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation . This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi **RAINA VENPOSH**

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CERTIFICATE

I hereby certify that the Project Dissertation titled "DAMAGE DISTRIBUTION AND BEHAVIOUR OF BUILDINGS IN BHUJ EARTHQUAKE-2001" which is submitted by Raina Venposh 2K21/STE/18 Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

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(Dr. Pradeep.K.GOYAL)
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ABSTRACT

The Bhuj earthquake of 2001 was a devastating natural disaster that resulted in significant damage to buildings and infrastructure in the Kutch district of Gujarat, India. The earthquake, which occurred on January 26, 2001, had a moment magnitude (Mw) of 7.7 and resulted in the loss of over 20,000 lives and widespread damage to buildings, roads, and other infrastructure. In the aftermath of the earthquake, there was a need to understand the distribution and behaviour of building damage to develop effective strategies for earthquake risk reduction. The objective of this project was to analyse the distribution and behaviour of building damage in the Bhuj earthquake of 2001, for understanding vulnerability of building typologies for future earthquakes.

To achieve this objective, ArcGIS was used to analyze the distribution of different building typologies in the study area, which included the talukas of Bhuj, Anjar, Bhachau, Rapar, Gandhidham, Mandvi, and Mundra in the Kutch district and Ahmadabad city. Damage data for building typologies was collected from various sources, including the Kutch collector office, GSDMA, and different blocks. The data were collected using various methods, including field surveys, remote sensing, and secondary data sources such as census and other government records. The data were then analysed to identify the distribution and behavior of building damage in the study area. The analysis revealed that the distribution and behavior of building damage varied significantly by building typology.

It has been found that the most vulnerable building typologies were adobe, mud, and timber buildings (KUTCHA), while reinforced concrete and steel buildings were less vulnerable to damage (PUCCA). Along with this the distribution of building damage was also influenced by several factors, including the proximity to the epicenter, the age and quality of construction, and the soil and geology of the area.

ACKNOWLEDGEMENT

I would like to express my sincere appreciation and gratitude to everyone who has contributed to the successful completion of this project. Although it may not be possible to name everyone who has helped me along the way, I would like to recognize some individuals for their exceptional support and guidance.

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Table of Contents

TABLE OF FIGURES

CHAPTER-1 INTRODUCTION

1.1 GENERAL

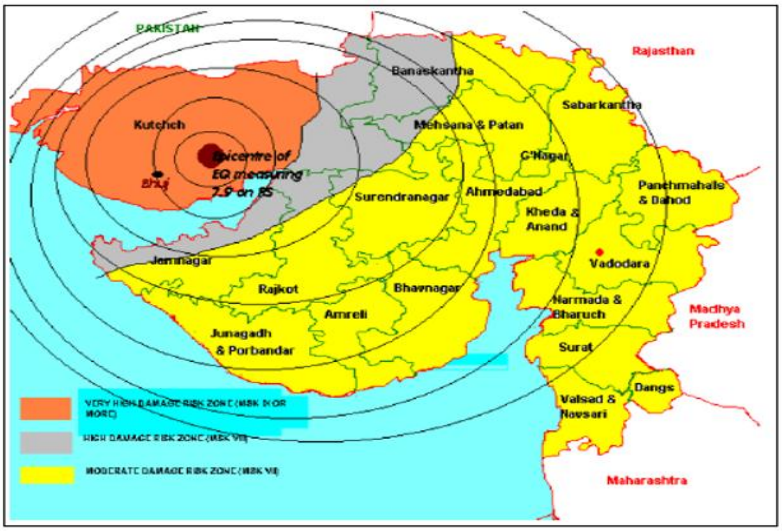
The Bhuj Earthquake was a natural calamity, which produced heavy losses to human lives including economic losses, of this devastating and unpredictable natural hazard in a few tens of seconds to a few minutes. The high concentration of population, buildings, and infrastructures exposed lead to most of the earthquake causalities due to building collapse and direct deaths in such catastrophic events. The Indian sub-continent is suffering from earthquakes since time immemorial. About 59% of Indian landmass is prone to moderate to severe earthquakes (BMTPC, 2006). As per seismic zoning map of India (BIS, 2016), India has been divided into four (4) seismic zones (Table 1) showing Modified Mercalli Intensity (MMI) corresponding to the seismic zones.

Table 1: Modified Mercalli Intensity (MMI) corresponding to the seismic zones

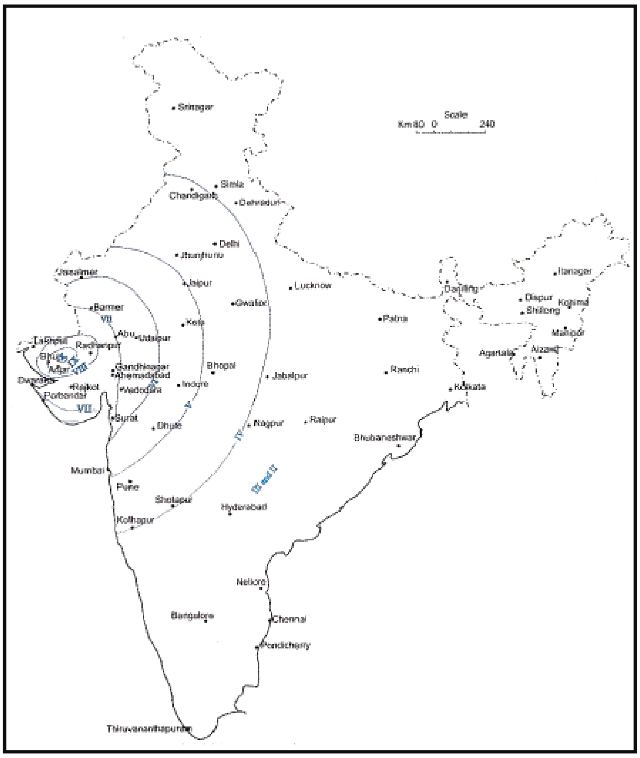
SEISMIC ZONE	POSSIBLE INTENSITY	Landmass Area (in %)
II (low)	VI and below	41
III (moderate)	VII	31
IV (severe)	VIII	17
V (very severe)	IX and above	11

On 26th Jan 2001 at about 08:46 hours (local time), a major earthquake occurred in the Bhuj district of Gujarat, which claimed about 13,805 human lives and caused severe damage to buildings, and infrastructure resulting in huge economic losses (Arya, 2000; Gupta and Gupta, 2001a; Gupta, 2007; NDMA, 2011). The epicenter of this earthquake at Chaubari village located to the North of Bhachau shaking the earth for approximately (110 seconds) leaving behind about 13,804 lives dead, 1,66,832 suffered injuries and affected 2,57,535 houses. Soon after the occurrence of this earthquake, a lot of controversies started about its magnitude. IMD reported its magnitude between 6.9, which was due to the local magnitude saturation. However, its moment magnitude (Mw) was 7.7 as reported by the USGS as well as its estimated magnitude strong motion local magnitude (M_L^{SM}) by Gupta and Gupta (2001b).

Due to the wide-reaching destruction, the Gujarat earthquake was designated as a national calamity. The impact of the earthquake was felt across a 400 km radius from its epicenter, causing significant damage to 21 out of 25 districts in Gujarat State. The districts of Kutch, Surrender Nagar, Paten, Banaskantha, Jamnagar, Rajkot, Ahmadabad, and Surat were particularly affected. The earthquake had a severe impact on 182 Talukas and 7,922 villages in the affected areas,.



Map 1: Gujarat Earthquake Damage Zones (Source: United Nations, 2001)



Map 2: Gujarat Earthquake Isoseismal map (Source: United Nations, 2001)

The earthquake's epicenter was situated at approximately 23.40 degrees North and 70.34 degrees East, with a focal depth of around 18 km. The location was about 70 km east of Bhuj city, in the foothills near the southern edge of the Banni plains. Although the earthquake did not result in a primary surface fault rupture, it caused significant liquefaction and slope failure across tens of thousands of square kilometres..

Table 2: IMD and USGS Earthquake parameters (IMD,2001), (USGS,2001)

Parameters	**IMD**	**USGS**
Date	26th Jan,2001	26th Jan,2001
Time	08Hrs 46Min42.9sec	08Hrs 46Min42.9sec
Magnitude	6.9	7.7
Focal depth(km)	25	18
Epicentre	23.242N, 70.017E	23.678N, 69.822E

1.2 OBJECTIVE AND SCOPE OF STUDY

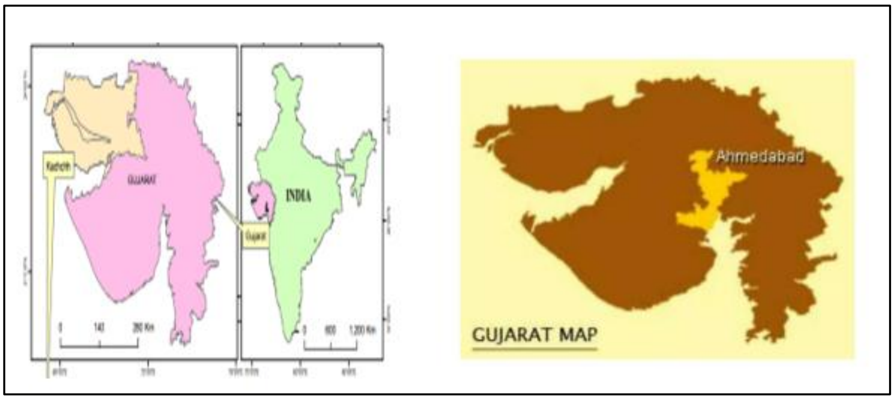
Following are the foremost objectives of the present study.

- Collect geospatial data on damage caused by the 2001 Gujarat earthquake.
- Identify building typology in the affected area and categorize them accordingly.
- Semi-quantify the damage by assigning a numerical value or rating to the level of damage observed.
- Aggregate the data at the lowest possible administrative boundary, such as village, tehsil, or district.
- Create visualizations and maps to represent the data collected, including the location and severity of damage, as well as the building typology.
- Analyze the data to identify patterns and trends in the damage and building typology.

1.3 STUDY AREA

The Bhuj earthquake of 2001, also known as the Gujarat earthquake, was a catastrophic event that struck the Kutch and Ahmedabad districts in the western Indian state of Gujarat. The earthquake, which had a magnitude of 7.7 on the moment magnitude scale, occurred on January 26, 2001, and caused extensive damage to buildings, infrastructure, and human life. From a structural engineering point of view, the Bhuj earthquake was a significant event that highlighted the importance of designing the earthquake resistant design and construction of buildings.The earthquake exposed the vulnerabilities of existing structures, particularly thos e that were not designed to withstand such a high magnitude earthquake. In the Kutch and Ahmedabad districts, many structures, including residential buildings, schools, hospitals, and other public infrastructure, were severely damaged or collapsed due to the earthquake.

This event led to a renewed focus on earthquake-resistant building design and construction practices in the region, as well as throughout India. In this thesis, the study area will focus on the Kutch and Ahmedabad districts, examining the structural engineering aspects of the Bhuj earthquake of 2001. The study will explore the damage patterns and failure mechanisms of various types of structures, as well as the lessons learned from the earthquake and their impact on building codes and standards. The goal of the present study is to provide a comprehensive analysis of the earthquake's impact on the built environment in the study area, and to identify best practices for earthquake-resistant design and construction in the future.



Map 3: Location map of the Study Area Kachchh and Ahmadabad district

Map 4: The sub-divisions of Kutch district are known as Kutch Talukas, as per the maps reworked andbased on the information from www.mapsofindia.com.

1.3.1 Location and Accessibility (Kachchh)

The Kachchh district of Gujarat, located between latitudes 22.72°-24.68° N and longitudes 68.10°-71.80° E, constitutes the Kachchh Peninsula in the westernmost part of India (as indicated in Map 3). The district covers an area of 45,612 sq km, with dimensions of approximately 320 km in length and 170 km in width. The Tropic of Cancer also runs through this district, which shares its western border with the delta land of Sindh (Pakistan). The focus of this study is on the Kachchh mainland fault, also known as KMF, which comprises five talukas in the Kachchh district of Gujarat: Bhachau, Rapar, Anjar, Gandhidham, and Bhuj. The Bhuj earthquake resulted in complete devastation of several towns in the region, including Bhachau, Anjar, Bhuj, Adipur, and Gandhidham. The vast majority of houses in the region, over 90%, are not engineered and do not comply with Indian Seismic Standards. Two-thirds of the population live in less durable "Kachchha" houses made of materials like mud, dung, adobe, and field stone, while the remaining third live in more durable "pucca" houses made of materials like cement mortar, brick, block, and cut stone. After the earthquake, the Gujarat State Disaster Management Authority (GSDMA) and other organizations evaluated the damage and classified buildings based on the IAEE Guidelines, but without specifying the construction type and probable cause of damage. According to estimates from IITB and EDM, 103,408 pucca houses and 65,781 kachchha houses collapsed. Although there were twice as many kachchha houses as pucca houses, the latter were more fatal. Several post-earthquake reconnaissance studies were conducted by researchers who identified the primary causes of failure, design, and construction deficiencies in particular housing types (such as those conducted by EERI, IITB and EDM, and GREAT). Damaged rural low-rise buildings can generally be grouped into four categories.

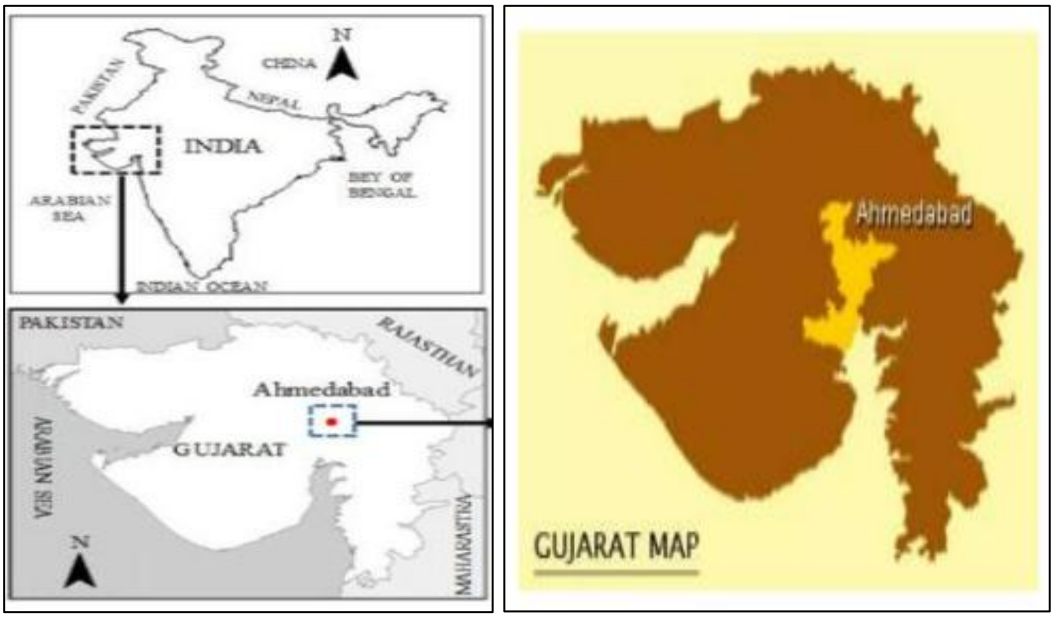
(1) Random rubble or stone masonry,

(2) Burnt brick or concrete block masonry,

(3) Adobe or mud, and

(4) Precast concrete panel

1.3.2 Location and Accessibility (Ahmedabad)



Map 5: Location map of the Ahmadabad district

The study area for the Ahmedabad chapter related to the 2001 earthquake would primarily focus on the impact of the earthquake on the city of Ahmedabad and its surrounding areas. The earthquake epicenter was approx 24Km north-west of Ahmedabad. The latitude and longitude of the epicenter were 23.38°N and 70.32°E, respectively. The city is well connected by air, rail, and road, and has an international airport that makes it accessible from other parts of the country and the world. However, the aftermath of the earthquake made accessibility challenging in some areas due to the damage to infrastructure and transportation networks. The area of the city of Ahmedabad is approximately 464 square Km, with a length of 20.6 Km and a width of 23Km. The dominant building typology in Ahmedabad is modern Reinforced concrete buildings and under reinforced masonry (URM), which is known to be vulnerable to severe earthquake ground motion.The earthquake caused extensive damage to buildings in the city, particularly those built using URM construction. The proximity of the Sabarmati River to the city could have had an impact on the damage caused by the earthquake, as liquefaction of the soil near the river can cause buildings to sink or collapse. The Sabarmati River flows through the western part of the city, with several areas of the city located in close proximity to the river. The Bhuj earthquake was caused by the movement of the Indian tectonic plate against the Eurasian plate along the Chaman Fault system. The depth of the earthquake was relatively shallow at about

18km, and the duration of the earthquake lasted for about two minutes. These factors, along with the proximity of the epicenter to a densely populated area, contributed to the severity of the earthquake and its impact on the region, including the city of Ahmedabad.

1.4 ORGANIZATION OF THE REPORT

Introduction: The first chapter of this thesis, titled "Introduction," provides an overview of the research study on the damage distribution and behavior of buildings in the Bhuj earthquake of 2001. It introduces the significance of the topic, the objectives of the study, and the methodology employed. The chapter also highlights the importance of understanding seismicity and tectonics in the region, as well as the need for collecting field data on damage.

Literature Review: The second chapter focuses on conducting a comprehensive literature review of existing studies and research related to seismic events, earthquake damage, and building behaviour. It explores various theories, models, and methodologies employed by researchers in similar studies, providing a solid foundation for the subsequent chapters.

Seismicity and Tectonics: In the third chapter, titled "Seismicity and Tectonics," the focus shifts to understanding the geological characteristics of the Bhuj region and the seismic activity it experiences. This chapter provides an in-depth analysis of the tectonic processes, fault lines, and seismic hazard assessment in the area, contributing to a better understanding of the earthquake's impact.

Damage Data Collected from the Field: Chapter four is dedicated to discussing the damage data collected from the field. It outlines the methodology used for data collection, including surveys, inspections, and interviews with affected individuals. The chapter presents a detailed analysis of the types of damage observed, their severity, and their distribution across the affected area.

Damage Details in Different Towns, Including Kutch District and Ahmedabad District: The fifth chapter delves into the specifics of the damage observed in different towns affected by the Bhuj earthquake, with a particular focus on the Kutch district and Ahmedabad district. This chapter provides a comprehensive overview of the building typologies affected, the extent of damage in each town, and the factors contributing to variations in damage patterns.

Repair and Retrofitting of Structures in Kutch District: Chapter six explores the repair and retrofitting efforts undertaken in the Kutch district following the earthquake. It examines the strategies, techniques, and materials used in the reconstruction and rehabilitation process. The chapter evaluates the effectiveness of these measures in improving the resilience of structures against future seismic events.

Conclusions and Future Scope of the Study: The seventh and final chapter, titled "Conclusions and Future Scope of the Study," summarizes the key findings of the research. It discusses the implications of the study's results, identifies any limitations encountered during the research process, and provides recommendations for future studies in the field of earthquake damage assessment and mitigation. This chapter serves as a culmination of the thesis, offering insights into the behaviour of buildings during the Bhuj earthquake and suggesting avenues for further research and practical applications.

CHAPTER-2 LITERATURE REVIEW

This study aims to identify the areas that are most vulnerable to earthquake damage and to determine the factors that contribute to the severity of the damage. Understanding the behavior of buildings during seismic events is crucial for mitigating earthquake risks. The researchers review various methodologies, such as observational studies, survey methods, site visits, GIS, satellite imagery, experimental investigations, and analytical investigations, that can be used to collect data on earthquake damage to buildings and infrastructure. The review indicates that the performance of buildings during an earthquake is influenced by several factors, including earthquake intensities, building construction and materials, building height, location of the building from the epicenter, foundation, age, and the presence of seismic retrofitting measures. The findings of this study can help policymakers and city planners to make informed decisions about building codes, regulations, and aid organizations to prioritize relief efforts and allocate resources more effectively to reduce the risk of earthquake damage in the future.

P.R. Dash et. al (2003) [1] aimed to examine the damage distribution and behaviour of buildings in the Bhuj earthquake. Observational and survey methods were used to collect data on the damage distribution and performance of buildings in the earthquake affected areas to determine the factors that influenced the damage to buildings. Results indicated that the damage to buildings was influenced by several factors such as soil type, foundation type, and building height and also the buildings with shallow foundations and those constructed on soft soil were more vulnerable to damage. It was also found that taller buildings experienced more damage than shorter ones.

S. Bhowmick and S.K. Jain (2002) [2] examines the behaviour of buildings during the Bhuj earthquake in India in 2001 and presented the case studies of various types of buildings, including reinforced concrete, load-bearing masonry, and masonry infill walls which includes field surveys and interviews with building owners and occupants to collect data on the damage and behaviour of the buildings the factors that contributed to the damage and collapse of buildings during the earthquake. Result indicated that buildings with masonry infill walls were particularly vulnerable to damage during the earthquake due to the lack of proper connections between the infill walls and the structural frame, which led to the walls becoming detached and causing the collapse of the buildings.

R. Kumar and S.K. Jain (2002) [3] examine the causes of building damage in the Bhuj earthquake and the methodology adopted were site visits, interviews, and surveys of damaged and undamaged buildings and the analysis were done on building type, age, height, construction materials, soil type, and seismic zone. Result indicated that building damage in the Bhuj earthquake was influenced by soil type, building age, and building materials. Buildings constructed on alluvial and clayey soils experienced greater damage than those constructed on rocky or sandy soils. Older buildings were also found to be more susceptible to damage than newer buildings. Additionally, buildings constructed with unreinforced masonry suffered the most damage compared to reinforced masonry and reinforced concrete structures.

M. Kumar and M.C. Haldar 2001 [4] aims to examine the damage to traditional buildings in the Gujarat earthquake of 2001 and mainly focused on buildings with load-bearing masonry walls and investigated the factors that influenced the level of damage in these buildings. Collection of data was done on the damage to traditional buildings from various sources, including field observations, surveys, and interviews with local resident and analyzed the data to identify patterns and factors that were associated with the level of damage in the buildings. Results shows that several factors such as building height, building materials, and foundation type influenced the level of damage in traditional buildings with load-bearing masonry walls. Taller buildings tended to sustain more severe damage than shorter buildings. Also, the buildings made of unreinforced brick masonry were more susceptible to damage than those made of stone masonry or reinforced concrete. Along with this the buildings with shallow foundations were more vulnerable to damage than those with deeper foundations.

S. Nagarajaiah and R. DesRoches (2002) [5] studied the building performance in the 2001 Bhuj Earthquake and a field Investigation was done which provides an analysis of the performance of buildings during the Bhuj earthquake in 2001 to identify the factors that influenced the damage to buildings during the earthquake. Methodology Adopted were conducting detailed surveys of damaged buildings in the affected areas and analyzed the data collected from the surveys to identify patterns and trends in building performance. It was found that the damage to buildings was influenced by factors such as soil type, building height, and building materials and the buildings constructed on soft soil were found to have experienced more severe damage compared to those on hard soil. Tall buildings experienced more damage than shorter ones, and buildings constructed with unreinforced masonry were more likely to collapse than those built with reinforced concrete. Additional factors that contributed to building damage are poor construction practices, lack of seismic design, and inadequate maintenance.

S. Kunnath and K. Sabnis (2002) [6] analysed on Earthquake Damage to Unreinforced Masonry Buildings in the 2001 Bhuj Earthquake and investigated how factors such as building height, building materials, and soil type influenced the level of damage observed in these buildings. The study includes the combination of field surveys, laboratory testing, and analytical modelling to assess the damage to unreinforced masonry buildings. Data were collected on 336 buildings in the region and analyzed the damage patterns based on building height, building materials, and soil type. It was found that buildings made of low-quality materials such as mud and stone were more susceptible to damage than those made of higher quality materials such as brick and concrete and it was also observed that taller buildings experienced more severe damage, with collapse being more common in buildings over three stories high. It was also highlighted that the influence of soil type on building damage, with buildings situated on soft soils being more likely to suffer damage than those on firmer ground. It is noted that soil amplification played a role in the severity of damage observed in buildings on softer soils.

S.K. Jain, R. Kumar, and P.R. Dash (2002) [7] investigated the building damage caused by the 2001 Gujarat earthquake and conducted a comprehensive field survey of the affected areas and collected the data on the damage sustained by buildings. The methodology involved using a damage index to classify buildings into four categories based on the extent of damage. Data collected on building height, building materials, and foundation type. Result showed that the damage to buildings was influenced by several factors. Building height was found to be a significant factor, with taller buildings suffering greater damage. Also, the buildings constructed with brick masonry suffered more damage than those constructed with reinforced concrete. Along with these the shallow foundations suffering more damage.

N. Krishnamurthy and S.K. Jain 2002 [8] studied the Behaviour of RC Buildings during the Bhuj Earthquake in 2001. Field surveys were conducted of the affected areas and data were collected on the characteristics of the buildings, including their height, age, materials, and foundation type and also conducted a visual inspection of the damage patterns in the buildings. Result indicated that the damage to the RC buildings was influenced by several factors, including the height of the building, the materials used in construction, and the type of foundation. Tall buildings were found to be more vulnerable to damage than shorter buildings, and buildings constructed with poor-quality materials were more likely to suffer damage. Buildings with shallow foundations were found to be more vulnerable to damage than those with deep foundations. Buildings constructed with proper seismic design and construction practices suffered less damage.

Shrivastava et al. in 2002 [9] aimed to analyse the distribution of building damage caused by the 2001 Bhuj earthquake in India using GIS (Geographic Information System). The study involved the collection of data through field surveys and satellite imagery. A building damage assessment was conducted by visually inspecting the buildings and categorizing them into five damage classes. The data was then integrated into GIS software to generate maps of the affected areas. The results showed that the damage distribution was not uniform, and areas with higher damage were found to be clustered. It was also found that the severity of the damage was dependent on factors such as soil type, building type, and age.

Guleria et al. (2012) [10] aimed to assess the seismic vulnerability of buildings in Bhuj city, India using GIS-based methodology which involved the creation of a database consisting of information related to the building type, construction materials, and age, which were collected through field surveys and interviews with residents. The database was then used to perform a seismic vulnerability assessment using the HAZUS-MH software. The results showed that most of the buildings in Bhuj city were vulnerable to earthquakes, with many of them classified as being at high risk. The vulnerability was found to be associated with the construction materials used, as well as the age and height of the buildings.

Bhardwaj et al. (2015) [11] conducted a case study on the Bhuj earthquake of 2001 to assess the damage caused to buildings using remote sensing and GIS techniques. The study aimed to provide a cost-effective and rapid means of damage assessment that could help in the timely allocation of resources for relief and recovery effort. It involved the acquisition of high-resolution satellite images of the affected area, which were then processed using various image processing techniques. The processed images were then classified into different categories based on the degree of damage observed on the buildings. It was found that the most severe damage was observed in the areas where the buildings were constructed using traditional materials such as mud and stone. It was also found that the damage was more severe in the older buildings as compared to the newer ones, which were constructed using modern construction techniques. The results of the study demonstrated the effectiveness of using remote sensing and GIS techniques for rapid and accurate damage assessment of buildings following earthquakes and recommended the use of these techniques in future disaster management efforts to ensure timely and efficient allocation of resources for relief and recovery efforts.

Sharma et al. (2017) [12] conducted a study on earthquake vulnerability and risk assessment of buildings in Bhuj city using GIS and remote sensing. The study aimed to identify the most vulnerable areas and buildings in Bhuj city and to provide recommendations for earthquake risk reduction. GIS and remote sensing techniques were used to collect data on building characteristics, geology, and topography to create vulnerability and risk maps for the city and conducted a field survey to validate their findings. The results showed that the most vulnerable areas in Bhuj city were those with high soil liquefaction potential and areas with soft soil. It was also found that buildings constructed with poor quality materials were at higher risk of damage during earthquakes. It was recommended to improve building codes and regulations, retrofitting existing buildings, and conducting public awareness campaigns on earthquake safety.

Sudhir K. Jain 2002 [13] investigates the building damage and human casualties resulting from the earthquake. A field survey was conducted in the affected region to assess the damage to buildings and infrastructure and the method used were stratified random sampling method to select 154 settlements for the study, which included rural and urban areas. The data was collected through a combination of field observations, interviews with local residents, and photographs. It was found that the earthquake caused extensive damage to buildings and infrastructure in the affected region. Of the

1,410,000 buildings in the study area, 786,107 were damaged or destroyed. The damage was more severe in urban areas, where 82% of the buildings were affected, compared to rural areas, where 53% of the buildings were affected. The earthquake also caused significant damage to roads, bridges, and other infrastructure. In terms of human casualties, Jain found that the earthquake caused a total of 20,005 deaths and 167,000 injuries. The mortality rate was highest in rural areas, where the infrastructure was less developed and rescue efforts were more challenging. The earthquake also had a significant impact on the local economy, with an estimated loss of $2.2 billion. The findings of the study can be used to inform future disaster planning and preparedness efforts in earthquake-prone regions.

Pankaj Agarwal and Manish Kumar 2003 [14] studied the performance of buildings during the 2001 Bhuj earthquake and investigated the damage to buildings caused by the 2001 Bhuj earthquake in India. A post-earthquake reconnaissance survey was conducted to collect data on the performance of buildings during the earthquake. The study focused on three types of buildings: unreinforced masonry (URM) buildings, reinforced concrete (RC) buildings, and steel buildings. Data was collected on the type of construction, number of stories, age, and damage level of each building and the ground motion intensity at the location of each building. It was found that URM buildings suffered the most damage, with many collapsing or experiencing severe structural damage. RC buildings generally performed better, but some suffered significant damage. Steel buildings performed the best, with little or no damage. It was also found that the ground motion intensity played a significant role in the damage level of buildings and the buildings located in areas with higher ground motion intensity generally suffered more damage than those in areas with lower ground motion intensity.

C.V.R. Murty (2002) [15] conducted a study on the" performance of reinforced concrete frame buildings during the 2001 Bhuj earthquake in India". The methodology involved the collection of field data from the affected areas, including building surveys, damage assessments, and material testing. The results indicated that the reinforced concrete frame buildings performed relatively well during the earthquake, with most of the damage occurring in the non-structural elements such as infill walls and partitions. However, the study also highlighted the importance of proper detailing and construction practices to improve the seismic performance of the buildings.

Jagadish et al. (2002) [16] conducted a study on the damage caused to masonry structures in the Bhuj earthquake, with the objective of identifying the key factors that contributed to the failure of these structures. The authors analyzed various types of masonry structures, including unreinforced brick masonry, stone masonry, and reinforced masonry, and found that the most common mode of failure was due to the lack of adequate lateral resistance. In addition, the authors noted that the use of substandard materials and poor construction practices also contributed to the failure of many structures.

AK. Singh, S. K. Tomar, and S. K. Dubey (2017) [17] conducted a study on "Earthquake Vulnerability Assessment of Existing Buildings in Gandhidham and Adipur City for vulnerability at (India)", The study used a detailed methodology for vulnerability assessment and provided important results and recommendations for earthquake-resistant design. The results indicated that a significant proportion of buildings in the two cities were vulnerable to earthquakes, with many buildings falling in the high and moderate hazard zones and also identified several key factors that contributed to the vulnerability of buildings, such as poor construction quality, lack of maintenance, and inadequate seismic design.

CHAPTER -3 SEISMICITY AND TECTONICS

3.1 INTRODUCTION

The Kachchh region in India is located between two major faults, namely the Nagar Parker fault to the north and the Kathiawar fault to the south. Numerous significant faults, including the Katrol Hill fault, Kachchh Mainland fault, Banni fault, Island Belt fault, and Allah Bund fault, have been identified within this region. The Bhuj earthquake, which occurred in this area, is particularly noteworthy because it impacted the entire depth range where rifted domains are seismically active. Understanding the seismic source characteristics of this earthquake is crucial not only for the Indian subcontinent but also for central and eastern North America. In stable continental interiors, a discernible contrast in seismic activity exists between rifted and non-rifted domains, with rifted domains experiencing larger and deeper earthquakes.

The January 26, 2001, Bhuj earthquake occurred in a stable continental interior within 350 km of the plate border, which is characterised by high seismicity. The earthquake occurred deep below the crust, causing a series of aftershocks that spanned the full depth of the crust. Although there is little indication of surface rupture, there is plenty of evidence of lasting ground deformation caused by lateral spreading. The earthquake occurred in an area with a relatively low historical seismicity, implying that it was a transition zone between stable and tectonically active areas. Several settlements were severely damaged by the earth shaking, and many structures fell. Both P- and S-waves had a strong and severe effect, with the first P motion producing fissures in the walls.

3.2GEOLOGY AND TECTONIC SETTING

The stable continental craton of peninsular India and the collision zone between India and Asia along the Himalaya plate boundary zone define the northern Indian tectonic framework. Based on numerous data, plate tectonic models imply that the Indian plate is migrating north relative to Asia at a pace of 20_+3 mm per yr (Bilham et al., 2001). While the majority of this convergence occurs along the Tibetan Plateau's southern border, localised zones of deformation inside the Indian plate also contribute to convergence, as evidenced by previous earthquakes like as the 1819 M 7.5-8 Kachchh earthquake, the 1956 M 6.0 Anjar earthquake, and the 2001 Mw 7.7 Bhuj earthquake. Although the Kachchh area has a lengthy history of tectonic and geological development that dates back to the Proterozoic (>700 Ma), the specifics of its structural evolution and stratigraphic evolution are still not well known. Despite being classified as a stable continental region (Johnston et al., 2001, 1996), the area's active geologic formations, high historical seismicity, and closeness to the Himalayan collision zone raise the possibility that it is really a transitional component of the plate boundary. The Aravalli-Delhi belt and other Proterozoic structural trends, as well as Mesozoic (245 to 66.4 Ma) Gondwana 1 age rift structures, are both present in the Kachchh area.

The division of Gondwanaland throughout the Mesozoic and Paleogene eras was caused by several tectonic events that occurred during the Proterozoic age, and the geological features in the epicentral region appear to be connected to earlier, deep-seated bedrock formations. The reactivation of Precambrian structures in both eastern India, represented by the Eastern Ghats trend, and western India, represented by the Dhar war trend, coincided with the rifting of Gondwana in the late Triassic or early Jurassic. Smaller rift systems including the Kachchh, Narmada/Surat, and Khambhat basins also formed at this time, with the Kachchh basin's extensional structures adhering to the Proterozoic Aravalli-Delhi trend. With the transition from Paleogene extensional tectonics, these formations were reactivated as a result of regional compressive stress in the Neogene, Quaternary, and Recent eras. The Indian/Eurasian collision being responsible for the transition from Paleogene extensional tectonics to Neogene contractional deformation. The collision of the Indian and Eurasian plates is the main cause of the current tectonic activity in India. The Asian plate is clashing with the Indian plate as it moves northward at a velocity of nearly half that of the Indian subcontinent, which is moving at a rate of 52 to 63 mm/year. The Himalayan Mountains were created as a result of this intercontinental collision, which also caused enormous crustal blocks to flow into southeast Asia and the Caspian Sea from the east and west, respectively. The rate of contraction at the western edge of the plate near the Himalayan Frontal Fault System and along the western boundary of the plate near the India/Pakistan border.

Around 20 to 25 mm/yr of contraction is occurring at the western edge of the plate, close to the India/Pakistan border, and along the Himalayan Frontal Fault System. These numbers are based on studies carried out by a number of academics, including Burgmann et al. (2001), Frey Mueller et al. (1996), and Bilham et al. (2001).

Table 3: list of the main tectonic events that have affected western India.

Time, Ma (Million Years before Present)	Tectonic Episode
0	Ongoing contraction of Kachchh region and development of fold and thrust belt.
10	
20	Himalayan orogen begins by 20 M*a* in Miocene to early Pliocene time; increase in subsidence rate of Surat Basin, contraction of Kachchh Basin begins.
30	
40	
50	Suturing of India complete by 49 M*a*; India collides with Eurasia around 50 to 66 M*a*.
60	Western India drifts across Deccan/Reunion hot spot around 66 M*a*; Deccan Trap basalt flows erupted. Seychelles separate from India about 63 M*a*; Narmada/Surat Basins develop.
70	
80	
90	Madagascar rifts from India/Seychelles block around 90 M*a*.
100	
110	
120	
130	Separation of India/Seychelles/Madagascar block from Antarctica/Australia/New Zealand block around 130 M*a*; opening of Khambat Rift occurs along extension of the West Coast fault on the Dharwar trend; Kachchh Rift grows wider.
140	
150	Initial separation to form east and west Gondwana; initial rifting occurs along the Dharwar trend of the west coast; initial opening of Kachchh Rift begins along the northeast trending Aravali-Delhi trend.

Cross-references to Figure 1 and Table 3 indicate that the regional map shows the current pattern of tectonic activity in India, while the table summarizes the multiple tectonic episodes that led to the fragmentation of Gondwanaland during the Mesozoic and Paleogene periods. The text also refers to the Kachchh, Narmada/Surat, and Khambhat basins as smaller rift systems that developed during the rifting of Gondwana.

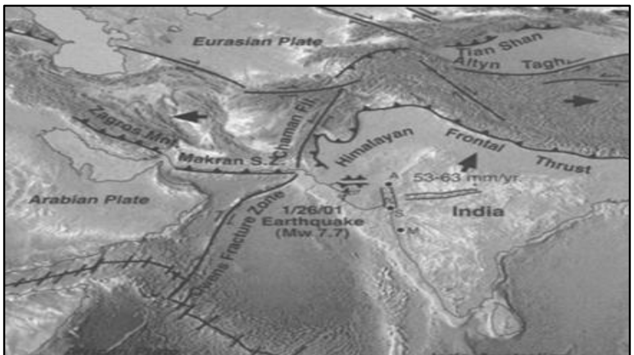


Figure 1: The Mw 7.7 Bhuj earthquake on January 26, 2001, occurred in northwestern India. The tectonic background of the earthquake was characterised by the displacement of crustal blocks, as represented by arrows representing large-scale motion.

The Bhuj earthquake, which took place less than 400 km from the western boundary of the Indian plate, was located at the junction of the Owens fracture zone, the Chaman fault, and the westernmost Himalayan Frontal Fault System. These structures collectively accommodate a relative motion of around 20 mm per year (**Figure 2**). The Makran subduction zone also terminates against these structures, making them a significant element of the tectonic framework of the region. The Neogene active Khambhat, Surat, and Kachchh grabens bound the epicentral region, as depicted on **Figure 3.** The Kachchh region is characterized by several structural features, including east-west-trending folds and faults, which deform Mesozoic clastic deposits and Deccan Trap basalts, Tertiary sedimentary units, possible Quaternary terrace surfaces and deposits, and alluvial/intertidal sediments.

The principal faults in the area are the east-trending Katrol Hill fault, Kachchh Mainland fault, Island Belt fault, Allah Bund fault, and Nagar Parker fault. Furthermore, the Kachchh region is bounded on the west by the Indus River Delta, which is one of the largest active alluvial depo-centers globally, containing more than 5 km of Tertiary to Recent sediment. The sediment loading resulting from the deposition of these sediments has been hypothesized as a mechanism for nontectonic crustal deformation in western and north western India. However, its role in the occurrence of the Bhuj earthquake is currently being investigated and remains uncertain (Whiting et al., 1994; Biswas, 1987; Rajendran & Rajendran, 2001; Malik, 2000; Merh, 1995).

Figure 2: The Gujarat and adjoining regions exhibit significant tectonic features, including the Nagar Parker fault, Allah Bund, Island Belt, Katrol Hill fault, Gulf of Kachchh, Recently, an earthquake took place slightly north of the Kachchh Mainland fault.

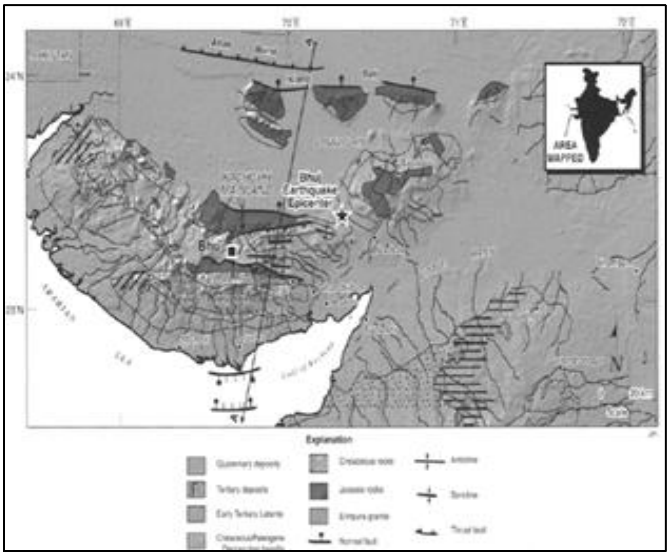


Figure 3: This image depicts a geologic map and cross-section location, utilizing data from Mehr's research in 1995. The map is accompanied by a topographic relief map, created using GTOPO30 data. The cross-section extends to the southeast across the Saurastra

3.2.1 Seismicity and tectonics of the Kachchh region

The research area pertains to the Kachchh region in the state of Gujarat, located in the north-western part of India. This state falls under seismic zone V, as per the seismic zoning map of India (BIS, 2002), indicating its vulnerability to seismic activity, with the potential to generate earthquakes up to magnitude 8. Within Gujarat, the Kachchh rift zone is the most seismically active region, having previously encountered two significant earthquakes of Mw7.7 in 1819 and 2001, respectively. (For reference, see BIS, 2002 and historical records of seismic activity in Gujarat.

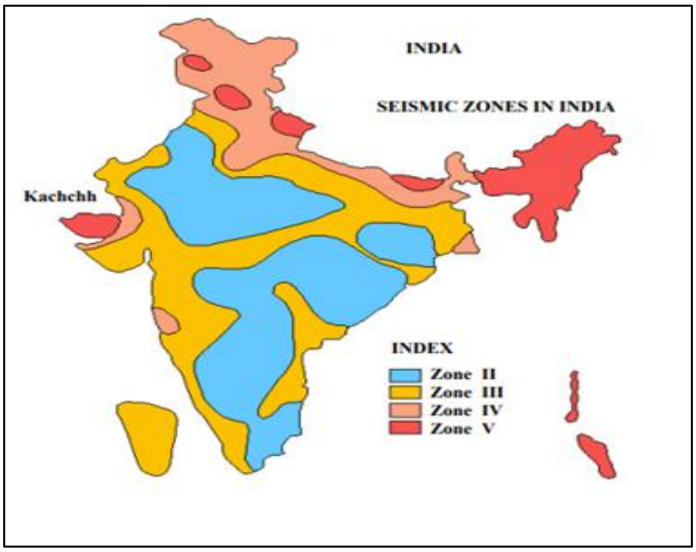


Figure 4: Seismic zones in India. (Source: Bureau of Indian Standard)

A seismic event with a magnitude of Mw6.0 called the Anjar earthquake, took place in 1956 towards the south of the epicenter of the 2001 Bhuj earthquake, which was also of moderate magnitude. (Chung and Gao, 1995). Rajendran and Rajendran (2001) have further documented 15 past and recent earthquakes of magnitudes between 5 to 6 that occurred in the same region. These findings are supported by previous studies (Chung and Gao, 1995; Rajendran and Rajendran, 2001).

The area has experienced two periods of rifting, occurring at 184 Ma and 88 Ma, respectively, as well as volcanic activity during the Cretaceous-Tertiary boundary Deccan volcanism at 65 Ma, when it passed over the Reunion hotspot. These events were documented in studies by Courtillot et al. (1986) and White and McKenzie (1995). Since 40 Ma, the region has been subject to compression due to the Himalayan collision, resulting in ongoing inversion tectonics. During the plate's drifting stage, horizontal stress was induced, causing near-vertical normal faults to become reactivated as reverse faults. The initiation of the inversion cycle led to the transformation of these faults into strike-slip faults involving divergent oblique-slip movements. This information was reported by Biswas (2005).

The oldest peri cratonic rift basin that emerged during the Late Triassic breakup of Gondwanaland is the Kachchh basin, which is situated on the western edge of the Indian plate (Biswas, 1987, 2005). The repeated reactivation of ancient faults in the Mid-Proterozoic Delhi fold belt caused the rift to widen from north to south (Biswas, 1987). Along the sub-vertical Nagar Parker and North Kathiawar faults (NPF & NKF), it is bordered to the north by the Nagar Parker uplift and to the south by the Kathiawar uplift (Saurashtra horst). The Island Belt, Kachchh Mainland, and Wagad uplifts, as well as three intra-rift faults called the Island Belt fault (IBF), Kachchh Mainland fault (KMF), and South Wagad fault (SWF), with intervening grabens and folds, are the three primary uplifts that make up the rift.

According to geological knowledge, the NKF is the primary bounding fault along which the rift subsided the most. It is believed that all faults in the area dip sub-vertically at an angle of 90° to 75° towards the adjacent half-graben or graben. In the eastern region, there is a significant uplift called the Wagad Uplift situated between the Island Belt and Mainland uplifts, which are tilted in opposite directions towards the north. The southern edge of the uplift is faulted with a narrow deformation zone. The backslope terminates at the Bela horst of the Island Belt uplift, while the Mainland and Wagad uplifts occur in an en echelon pattern. Biswas and Khattri (2003) proposed that the KMF and SWF are components of a left-stepping dextral strike-slip fault system. Biswas (2005) further supports this idea by suggesting that the SWF is the eastward continuation of the KMF after side-stepping, with an overlap zone between Bhachau and Adhoi.

The Median High, a subsurface basement ridge in the Kachchh rift zone, separates the basin into a shallower and more tectonized eastern portion and a deeper western portion. The Radhanpur Arch, a transverse subsurface basement ridge that acts as a stress barrier for eastward motions, is where the rift also comes to an end in the east. The proximity of the epicentres of the 1956 Anjar (Mw6.0) and 2001 Bhuj (Mw7.7) earthquakes, as well as the concentration of aftershock hypocentres, show that this region is the most favourable location for rupture nucleation. Sen et al. (2009) also noted the presence of volcanic rocks invading the Mesozoic sediments during rifting, followed by a post-rift hotspot associated with the Deccan volcanism.

The estimated depth of the Moho has been shown to vary significantly in previous studies utilising seismic refraction data in the Kachchh area, ranging from 37 to 45 km (Reddy et al., 2001). The crustal (36-42 km) and asthenosphere (62-77 km) strata under the Kachchh rift zone, in contrast to the surrounding unrifted regions, have thinned, according to a more recent combined inversion of P-receiver functions and surface wave group velocity dispersion data (Mandal, 2012). The Kachchh crustal structure appears to be made up of several heterogeneous blocks that are divided by a number of deep crustal faults with an E-W trend that go all the way down to Moho depths. A dominating compressive regime with almost N-S trending P-axes is also indicated by focal mechanism solutions for earthquakes in the Kachchh area (Antolik and Dreger,

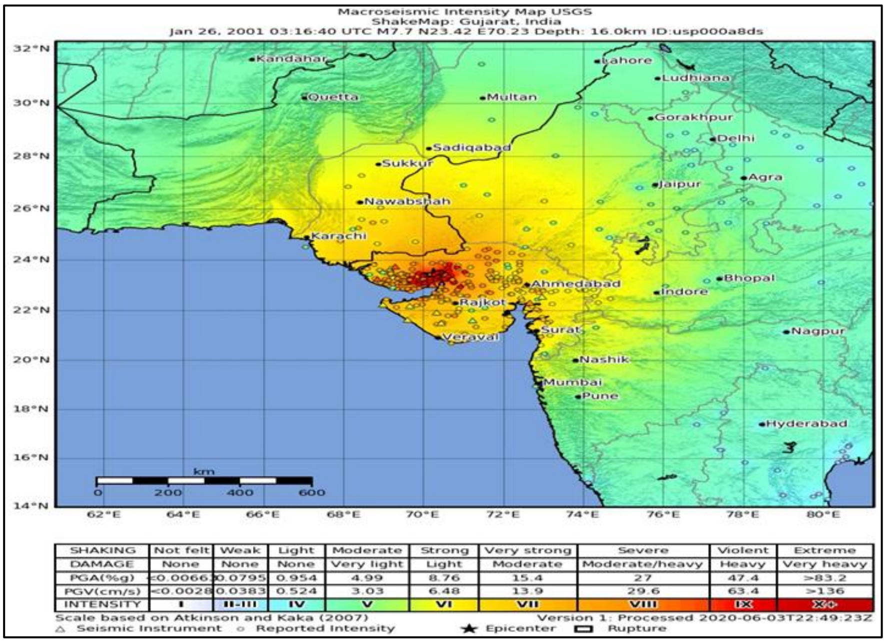


Figure 5: USGS SHAKEMAP (BHUJ EARTHQUAKE 2001)

A shake map is a visual representation that displays the intensity of ground shaking caused by an earthquake, using recorded ground motion data such as peak velocity and acceleration obtained from instruments.

CHAPTER-4 DAMAGE DATA COLLECTED FROM FIELD

4.1 METHEDOLOGY ADOPTED

The process of preparing a map involves various stages of Data collection, Data preparation, and Data analysis to produce various representations of Damage information and Geographic information. The Flowchart provides clear information on the steps involved in this process.

The first step is to collect the necessary data on the building typology which consists (of Kutcha houses, Pucca houses, and Huts). Population data (census 2001) and casualty data such as deaths and injuries from the field for the Bhuj earthquake in 2001. This data can be obtained from various sources such as government records, census data from 2001, news reports, and other relevant publications/ Journals. Once the data is collected it needs to be cleaned and prepared for analysis. The data should also be formatted in a way that is suitable for analysis in ArcGIS software. Using the ArcGIS software, the collected data can be analyzed for identifying patterns and damaging trends. The following steps can be followed for analyzing the data.

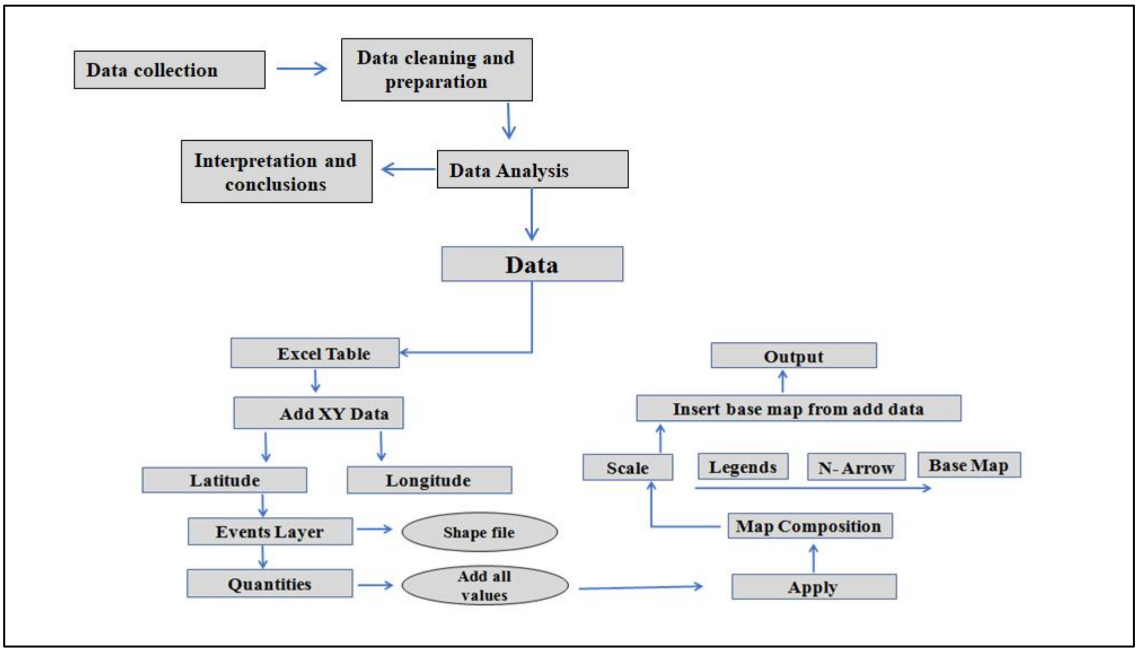


Figure 6: Flowchart of the Methodology

- **Data Collection:** The initial stage involves collecting locational data, which can be obtained through various sources, such as surveys, satellite images, and aerial photographs.
- **Data Processing:** The collected data is processed into layers files, which can be imported into the mapping software. The layers files are further processed into shapefiles for compatibility with the software.
- **Layer Analysis**: After importing the data into the software, the user selects the layer properties to analyze and determine the appropriate thematic tools and techniques to represent the attribute data in graphical form.
- **Thematic Mapping**: The thematic tools and techniques can include choropleth maps, dot density maps, and heat maps, among others. These tools help to represent the attribute data in a graphical presentation that is easy to interpret.
- **Map Composition**: After applying the thematic tools and techniques, the user can begin the process of map composition. This involves creating a visual layout that includes all the necessary components of a map, such as a North arrow, legend, scale, title, and the base map, which represents the neighboring areas for better understanding.
- **Output:** The final output is presented as maps that provide a visual representation of Damages in houses, population density, and casualty information.

4.2 TABLES AND MAPS

Based on the above methodology I have created tables and thematic maps in ArcGIS.

- Population distribution maps at district level.
- Damage distribution maps of building typologies at district level.
- population density maps at taluka level of kutch district (study area).
- Damage distribution maps of building type and %damage at each talukas of Kutch district.
- Deaths and Injuries map at district and Taluka level.

4.2.1 Damage distribution data table of Gujarat

Level	Name	Latitude	Longitude	Total pop(1991)	Affected(pop)	Male(M)	Female(F)	Total pop(2001)	Deaths(M)	Deaths(F)	Deaths(child)	Deaths(total)	Death(%)	Injuries
District	**Kacchch**	**29.733**	**69.8597**	**1262507**	**1262507**	**782335**	**743986**	1526321	**3229**	**4573**	**4419**	**12221**	**0.967994633**	**136048**
taluka	Anjar	23.117	70.019	160640	160640	82583	77709	160292				3741	2.328809761	
taluka	Bhuj	23.245	69.662	277215	277215	177232	167781	345013				2500	0.901827102	
taluka	Bhachau	23.287	70.352	114759	114759	76566	71325	147891				4696	4.092053782	
taluka	Rapar	23.576	70.641	150517	150517	102674	95326	198000				561	0.372715374	
taluka	Gandhidham	23.074	70.131	104585	104585	106564	95005	201569				707	0.676005163	
District	Ahmedabad	23.03	72.4	4687491	3894000	3069861	2738517	5808378	290	244	218	752	0.019311762	4060
District	Rajkot	22.18	70.56	2514122	1594000	1635741	1521935	3157676	106	204	119	429	0.026913425	11951
District	jamnagar	22.27	70.07	1563558	1563000	985266	928419	1913685	28	62	29	119	0.007613564	4930
District	Surat	21.17	72.83	3397900	397989	2722675	2273716	4996391	25	9	12	46	0.011558108	190
District	Surendranagar	22.43	71.43	1208872	1154000	787785	727362	1515147	26	46	38	110	0.009532062	2909
District	Banaskantha	24.34	71.76	2013519	719000	1296415	1206428	2502843	9	13	10	32	0.004450626	2770
District	Kheda	22.45	72.45	1793138	35121	1052869	970485	2023354	0			0	0	28
District	Bharuch	21.41	73.01	1148052	460000	713475	656629	1370104	3	4	2	9	0.001956522	44
District	Gandhinagar	23.21	72.63	1026728	35000	698360	636371	1334731	2	0	6	8	0.022857143	241
District	Patan	23.52	72.1	935203	664000	611486	570455	1181941	11	13	14	38	0.005722892	1695
District	Junagadh	21.31	70.36	2018446	597787	1252458	1195969	2448427	1	4	3	8	0.001338269	89
District	Navsari	21.07	73.4	1085692	87783	628814	600436	1229250	7	6	4	17	0.019365936	52
District	Porbandar	21.37	69.49	376113	376113	275921	260933	536854	4	3	3	10	0.002658775	90
District	Vadodra	22	73.16	3039127	186092	1896859	1742916	3639775	0	1	0	1	0.000537369	270
District	Bhavnagar	21.46	72.11	2060315	445226	1275329	1193935	2469264	2	1	1	4	0.00089842	45
District	Anand	22.32	73	1647759	4687	972355	884357	1856712	0	1	0	1	0.021335609	20
District	Mehsana	23.42	72.37	1648251	1648251	954006	883690	1837696	0	0	0	0	0	1339
District	Sabarkantha	23.84	72.99	1761086	128000	1069602	1013814	2083416	0	0	0	0	0	56
District	Amreli	21.36	71.15	1484300	599000	701384	691911	1393295	0	0	0	0	0	5
District	Valsad	20.59	72.93	1087680	5985	734945	675735	1410680	0	0	0	0	0	0
TOTAL				37759859	15857541	24117941	22117999	46235940	3743	5184	4878	13805	0.087056373	166832

injuries (%)	Pucca house damaged(<75%)	Kuccha house damaged(<75%)	uts damaged(<75%	Total houses damaged	Pucca house destroyed(>90%)	Kuccha house destroyed(>90%)	Huts destroyed(>90%)	Total house destroyed	Total houses destroyed or damaged
10.77601946	**72171**	**34968**	**0**	**107139**	**84615**	**65781**	**0**	**150396**	**257535**
0.104262969	19451	1982	1713	23146	814	130	154	1098	24244
0.749749059	59384	36407	4065	99856	22102	18727	1031	41860	141716
0.315419066	63081	18225	5780	87086	19082	4152	2433	25667	112753
0.047740013	1197	20	5	1222	30	0	2	32	1254
0.252079723	62517	76779	5454	144750	13266	14704	590	28560	173310
0.385257302	1119	5903	109	7131	122	1447	280	1849	8980
0.079724381	776	87	285	1148	46	8	20	74	1222
0.009565217	73	4488	1264	5825	39	860	95	994	6819
0.688571429	5342	42	11	5395	0	1	2	3	5398
0.255271084	12147	14116	9382	35645	2725	2247	8793	13765	49410
0.014888246	4126	7453	20	11599	137	269	9	415	12014
0.059236982	2200	0	14	2214	98	0	0	98	2312
0.023928979	8886	6732	43	15661	1570	1178	17	2765	18426
0.145089526	21	120	5	146	0	0	18	18	164
0.010107226	8453	1565	992	11010	547	541	188	1276	12286
0.426712183	320	484	0	804	13	2	0	15	819
0.081237627	190	432	33	655	22	17	2	41	696
0.04375	31	53	0	84	0	1	0	1	85
0.000834725	3857	4809	0	8666	121	316	2	439	9105
0	70	0	2	72	1	0	0	1	73
1.052067278	**325412**	**214665**	**29177**	**569254**	**145350**	**110381**	**13636**	**269367**	**838621**

4.3 DAMAGE ASSESSMENT

The Bhuj earthquake of 2001, commonly referred to as the Gujarat earthquake, was a catastrophic quake with a magnitude of 7.7 on January 26, 2001. Buildings and infrastructure in the area sustained substantial damage as a result of the earthquake, especially in the cities of Bhuj, Anjar, Rapar, Gandhidham, Bhachau, and Ahmedabad.

Table 4: IAEE Damage classification number of Houses (kachchh district) in Each classes

injuries (%)	Pucca house damaged(<75%)	Kuccha house damaged(<75%)	uts damaged(<75%	Total houses damaged	Pucca house destroyed(>90%)	Kuccha house destroyed(>90%)	Huts destroyed(>90%)	Total house destroyed	Total houses destroyed or damaged
10.77601946	**72171**	**34968**	**0**	**107139**	**84615**	**65781**	**0**	**150396**	**257535**
0.104262969	19451	1982	1713	23146	814	130	154	1098	24244
0.749749059	59384	36407	4065	99856	22102	18727	1031	41860	141716
0.315419066	63081	18225	5780	87086	19082	4152	2433	25667	112753
0.047740013	1197	20	5	1222	30	0	2	32	1254
0.252079723	62517	76779	5454	144750	13266	14704	590	28560	173310
0.385257302	1119	5903	109	7131	122	1447	280	1849	8980
0.079724381	776	87	285	1148	46	8	20	74	1222
0.009565217	73	4488	1264	5825	39	860	95	994	6819
0.688571429	5342	42	11	5395	0	1	2	3	5398
0.255271084	12147	14116	9382	35645	2725	2247	8793	13765	49410
0.014888246	4126	7453	20	11599	137	269	9	415	12014
0.059236982	2200	0	14	2214	98	0	0	98	2312
0.023928979	8886	6732	43	15661	1570	1178	17	2765	18426
0.145089526	21	120	5	146	0	0	18	18	164
0.010107226	8453	1565	992	11010	547	541	188	1276	12286
0.426712183	320	484	0	804	13	2	0	15	819
0.081237627	190	432	33	655	22	17	2	41	696
0.04375	31	53	0	84	0	1	0	1	85
0.000834725	3857	4809	0	8666	121	316	2	439	9105
0	70	0	2	72	1	0	0	1	73
1.052067278	**325412**	**214665**	**29177**	**569254**	**145350**	**110381**	**13636**	**269367**	**838621**

Different types of buildings in these cities experienced varying levels of damage, depending on the construction materials and design. The three main building typologies that were assessed were kutcha houses (made of non-engineered materials such as mud and thatch), pucca houses (made of engineered materials such as brick and concrete), and huts (temporary structures made of non-engineered materials). The damage to these building typologies was classified into five damage states: G1,G2, G3, G4 and G5. The following table shows the different damage states and corresponding numbers for each building typology in each location:

Table 5: Different damage states and corresponding numbers

Damage Category	No. Houses*	Walls	Roofs/Floors
G1- slight Nonstructural	19,229	Thin cracks in plaster, falling of Plaster bits in limited parts.	Thin cracks in small areas, roofing tiles only slightly disturbed.
G2- slight Structural	15,104	Small cracks: falling of plaster in Large areas, damage to nonstructural parts(e.g: parapets)	Small cracks in slabs, AC sheets; 10% tiles disturbed, minor damage Understructure of sloped roofs.
G3- Moderate Structural	18,059	Large and deep cracks; Widespread cracking of walls columns and piers or collapse of One wall;load carrying capacity of structure partially reduced.	Large cracks in slabs; some AC sheets broken;up to 25% tiles Disturbed/fallen; moderate damage to understructure of sloping roof.
G4- severe Structural	20,458	Gaps occur in walls; two or more Inner or outer walls collapse;50% Of main structural elements fail; Building in dangerous state.	Floors badly cracked, part may fail; Understructure of sloping roof heavily damaged, part may fail; tiles badly affected, fallen.
G5- Collapse	96,339	Large part or whole building Collapsed.	Large part or whole floor and roof collapse or hang precariously.

To evaluate the magnitude of physical harm to structures, buildings were inspected and categorized into five damage classifications: G-0 (no damage), G-1 (minor non- structural damage), G-2 (minor structural damage), G-3 (moderate structural damage), G-4 (serious structural damage), and G-5 (collapsed).

Table 6: Damage statistics in towns of Kachchh district (Source: Jain et al., 2002: 306)

Town	Distance from Epicenter	Percentage of Buildings in each Damage Category				
		G-1	G-2	G-3	G-4	G-5
Bhachau	13 km	0.0	0.0	0.9	0.7	98.4
Rapar	33 km	3.1	11.2	21.0	31.9	32.7
Anjar	41 km	35.5	12.7	12.7	6.7	32.4
Gandhidham	44 km	47.4	22.6	12.9	8.5	8.5
Bhuj	63 km	16.0	19.2	18.3	20.5	25.7
Total		29.2	17.4	14.1	13.1	26.2

According to **Table 6**, the level of damage in Bhachau was predominantly severe, with over 95% of affected buildings classified in the G-5 category. In contrast, in Bhuj, nearly 50% of buildings were in a badly damaged or collapsed state (G-4 and G-5), while the other 50% were partially damaged but still standing. Based on this table, separate damage categories were created for pucca houses and kaccha houses, which are presented in **Table 7** and **Table 8**, respectively. The choice of masonry material used in construction varies across the Kachchh region and is primarily influenced by availability and cost. Stone is the most commonly used material in the Rapar area, while micro concrete blocks and fired bricks are prevalent in the Bhuj area. In the Bhachau area, fired bricks are the dominant construction material.

Table 7: Damage distribution data of Kachchh Talukas (source: Damage survey data provided by GSDMA, Disaster Management cell BHUJ)

Kutch Talukas Damage Distribution Data												
Level	Name	Latitude	Longitude	Totalpop	Male	Female	Deaths(total)	Death(%)	injuries	Pucca Houses	Kuccha houses	Total Houses
District	Kacchch	29.733	69.85	1526321	782335	743986	12221	0.967995	136048	103408	65781	169189
Taluka	Anjar	23.117	70.019	160292	82583	77709	2529	2.32881	2105	16807	9807	26614
Taluka	Bhuj	23.245	69.662	345013	177232	167781	2959	0.901827	2794	17063	15132	32195
Taluka	Bhachau	23.287	70.352	147891	76566	71325	4712	4.092054	2162	43392	25220	68612
Taluka	Rapar	23.576	70.641	198000	102674	95326	602	0.372715	102	24865	9417	34282
Taluka	Gandhidham	23.074	70.131	201569	106564	95005	816	0.676005	93	1281	6205	7486

The earthquake caused destruction to about 70% of the buildings in Kachchh, with the highest casualties occurring within the walls of Bhuj and Anjar, which had previously suffered damages during the 1819 earthquake. Repairs and reconstruction of the historic buildings were carried out at the same sites, but lack of maintenance and use of heavy masonry work with inadequate through-stones also contributed to the earthquake damage, according to Jain et al. (2002). Villages that experienced severe damage mainly used masonry construction with random rubble and mud mortar, which offered poor shear strength, resulting in the construction of thicker walls up to 750 mm. In Kachchh, semi-dressed stones of 600 mm x 400 mm x 250 mm were utilized in stone masonry, contrary to the typical Indian practice of using stones with a maximum dimension of 400 mm, with an 80-mm-thick mortar.

The collapse of a considerable portion of the large-block masonry above can put the safety and stability of the whole building at risk, in case one stone becomes dislodged out-of-plane due to intense seismic shaking.

Table 8: Damage category of Pucca houses in talukas of Kachchh

Distribution of pucca houses in each damage category						
Talukas	G1	G2	G3	G4	G5	Pucca houses
Bhachau	0	0	391	304	42697	43392
Rapar	771	2785	5226	7932	8151	24865
Anjar	5966	2134	2134	1127	5446	16807
Gandhidham	608	291	166	108	108	1281
Bhuj	2730	3276	3122	3519	4416	17063
Total	10075	8486	11039	12990	60818	**103408**

Table 9: Distribution of Pucca houses as per damage category

Distribution of pucca houses in each damage category						
Talukas	G1	G2	G3	G4	G5	Pucca houses
Bhachau	0	0	391	304	42697	43392
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Anjar	5966	2134	2134	1127	5446	16807
Gandhidham	608	291	166	108	108	1281
Bhuj	2730	3276	3122	3519	4416	17063
Total	10075	8486	11039	12990	60818	**103408**

Table 10: Damage category of kuccha houses in talukas of Kachchh

Damage category of Kuccha Houses-Kutch						
Talukas	G1	G2	G3	G4	G5	Kuccha houses
Bhachau	0	0	227	176	24817	25220
Rapar	292	1064	1977	3004	3080	9417
Anjar	3481	1245	1245	658	3178	9807
Gandhidham	2943	1404	802	528	528	6205
Bhuj	2438	2905	2769	3102	3918	15132
Total	9154	6618	7020	7468	35521	**65781**

Generally, we have divided building typologies into three categories that is **pucca houses** (generally constructed from durable materials such as cement, concrete, and brick), kutcha **houses** (constructed from adobe mud, dung, and field stone or other less durable materials ,and **huts** (temporary structures made of non-engineered materials).

Kutcha houses are typically made of mud, bamboo, thatch, and other locally available materials. These structures are vulnerable to earthquakes, as they lack the strength and durability of more modern building materials. In Bhuj, many kutcha houses collapsed during the earthquake, resulting in significant loss of life, particularly in rural areas.

Pucca houses, on the other hand, are constructed using more durable materials such as bricks, concrete, and steel. These structures are better equipped to withstand earthquakes, but their resistance depends on the quality of construction and adherence to building codes. In Bhuj, many pucca houses suffered damage, with some collapsing entirely.

Huts are similar to kutcha houses, but they are usually smaller and more temporary structures. They are typically used as shelters by migrant workers and the urban poor. In Bhuj, many huts were destroyed during the earthquake, leaving their occupants homeless and vulnerable.

1. **Random Rubble Masonry**

In India, the practise of building with stone or random debris and mud mortar was quite popular and extremely dangerous. Often, broad walls made of two wythes are constructed using uneven stones set in flimsy mortar. The mortar's weak tensile strength, which was readily exceeded in the powerful earthquake and led to walls separating at corners and T-junctions, is this style of construction's main shortcoming. Separation and collapse were facilitated by the lack of through stones or shear connections between parallel wythes. Additionally, the walls are frequently constructed one at a time, leading to a weak connection at the corner.

2. **Brick and Concrete Block Masonry**

Similar factors, such as brittle mortar and insufficient connections, led to catastrophic failures of load-bearing concrete block and burned brick masonry structures. The kind and connectivity of the roof had an impact on the degree of damage for masonry constructions. The walls were improperly attached to the roofs, which resulted in a reduction in the transfer of roof inertial forces to the walls and increased the likelihood of roof collapse due to subpar or improperly protected wood, heavy stone slab, or concrete roofs. Buildings with lighter roofs often sustained less damage than those with heavy roofs. Ceramic roof tiles that weren't attached to the wooden battens went loose and fractured in this situation..

3. Mud or Adobe (Bhungas)

A bhunga is a traditional, typically circular plan structure made of mud bricks or an interior matrix of tree branches packed with mud. The roof is supported by a vertical post resting on a single wooden beam that sits on the walls. Bhungas performed comparatively well during the earthquake.

Shell action of the wide, low circular walls distributes the shear forces. Some bhungas have ring beams or some kind of connection between the roof and the walls. According to IIT and EDM , the primary cause of damage was collapse of the vertical post and roof. The walls usually collapsed outward.

4. Precast Concrete Panels

Precast concrete panels were used by the Government of Gujarat to build 6000 primary schools throughout the state (IIT and EDM). These buildings performed very poorly because the panels, in both the walls and roofs, were connected using a tongue-in-groove system without dowels, allowing the connections to simply open up and the panels to separate during the earthquake.

5. Soils and Foundations

Kachchh is covered in black cotton soil, a very expansive clay, which may have contributed to the pre-earthquake damage to fragile masonry buildings. Additionally, loose alluvial soils in flood basins and coastal locations led to excessive settlement and loss of bearing support (GREAT). Rural structures in Kachchh are typically inadequately grounded on thin, loose stone strip footings. Differential movement of isolated spread footings has hastened damage to precast panel structures.

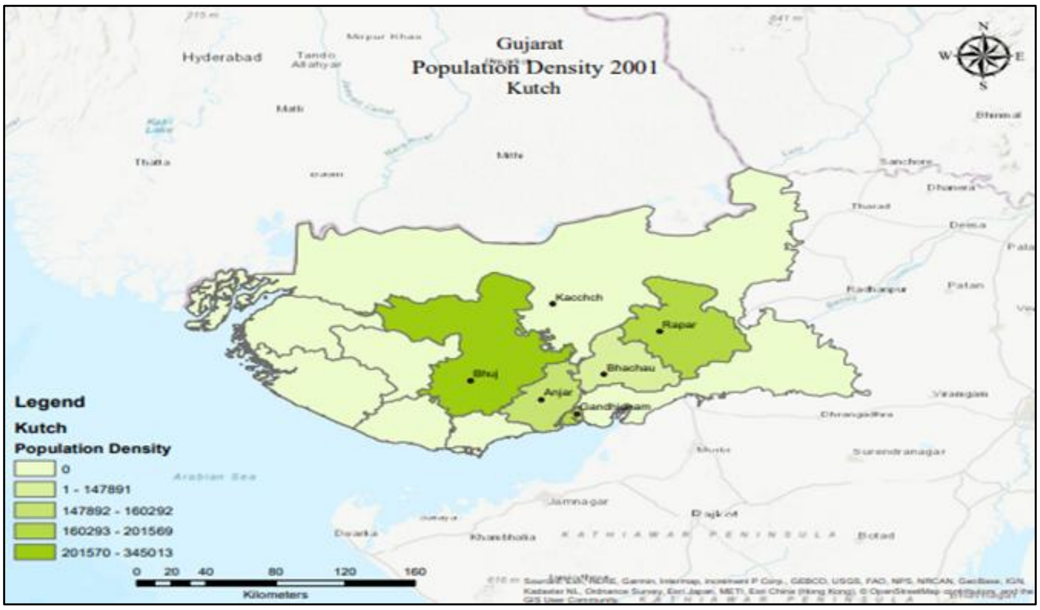
6. Seismic Bands

Masonry buildings with reinforced concrete seismic bands at the lintel and sill levels performed well during the earthquake. Damage was limited to minor cracks near the corners and along the lintel bands.

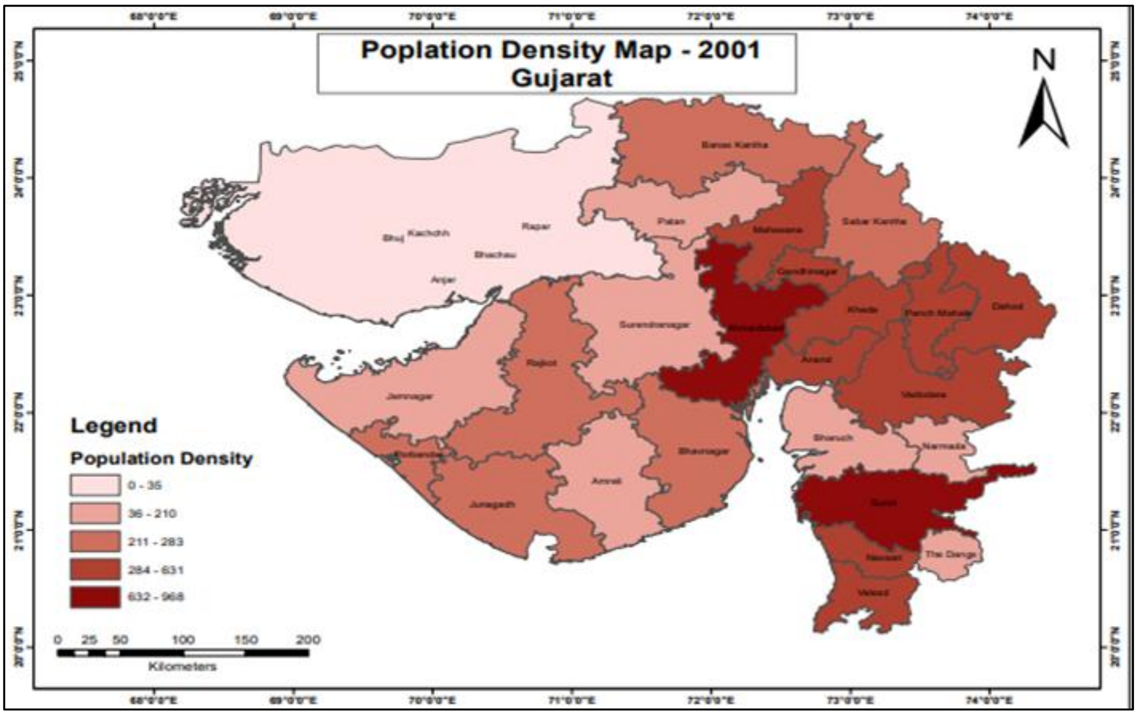
Figure 7: Rubble masonry with concrete roof and Seismic bands

Figure 8: Bhunga

4.4 Population density Kutch- 2001



4.4.1 Population Density Map -2001 Gujarat



The map referred to is known as a population density map. It is a type of thematic map that focuses on the distribution of people over a specific geographical area, highlighting areas with higher or lower population densities. Population density is a measure of the number of people per unit of area, typically expressed as the number of individuals per square mile or kilometre. To create a population density map, the total population of a particular geographic area, such as a city, state, or country, is divided by the total land area of that region. The resulting value is then used to create a color-coded or shaded map that shows the population density of different areas. In population density maps, areas with higher population densities are typically represented using darker shades of colour, while areas with lower population densities are represented using lighter shades.

Bhuj, for example, had a population density of 138 people per square kilometer in 2001. While this is not as dense as some of the other cities on the list, it is still a significant population concentration. The earthquake that struck Bhuj on January 26, 2001, was measured at a magnitude of 7.7 and had a devastating impact on the city and its surrounding areas, leading to extensive damage to buildings, roads, and other infrastructure.

Anjar, with a population density of 363 people per square kilometer, was also heavily impacted by the earthquake. The city is located approximately 41 kilometers from Bhuj and experienced significant damage to its buildings and infrastructure as well.

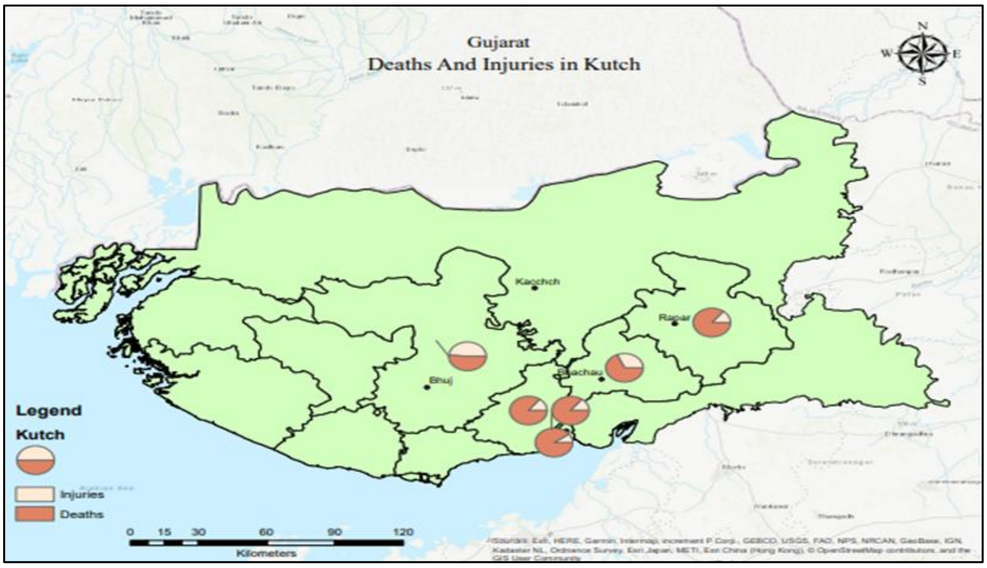
Rapar has a population density of 118 people per square kilometer and is approximately 33 kilometers from Bhuj. While it was not as heavily impacted as Bhuj or Anjar, the earthquake still caused damage to buildings and infrastructure in the city.

Gandhidham, with a population density of 443 people per square kilometer, is located approximately 44 kilometers from Bhuj. While the city did experience damage from the earthquake, it was not as severely impacted as Bhuj or Anjar due to its distance from the epicenter of the quake.

Bhachau, with a population density of 177 people per square kilometer, is located approximately 13 kilometers from Bhuj. The city was also impacted by the earthquake, and many buildings and other structures were damaged or destroyed.

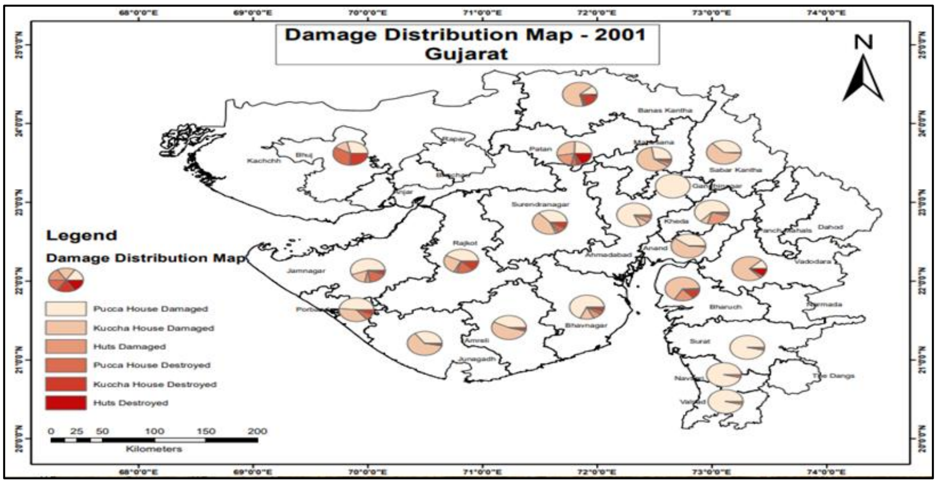
Ahmedabad has a much higher population density of 983 people per square kilometer and is approximately 238 kilometers from Bhuj.

4.5 DEATHS AND INJURIES IN KUTCH -2001

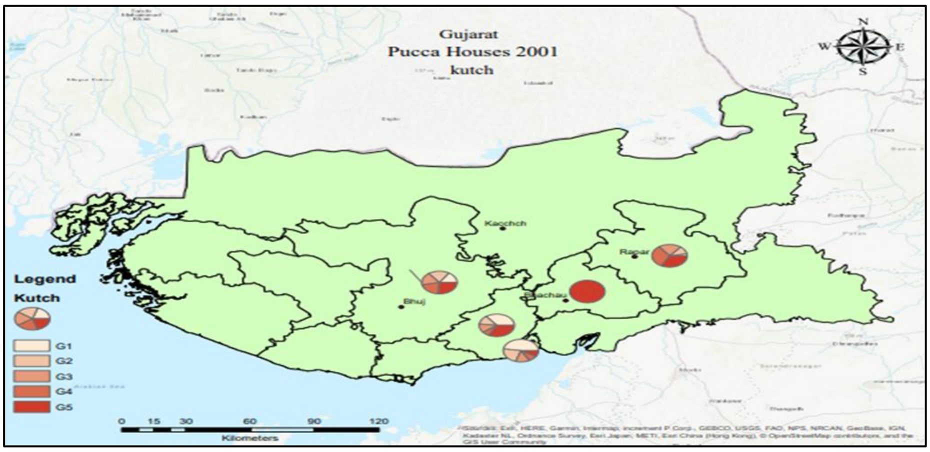


This map represents the deaths and injuries that occurred during the disaster and through the pie chart; we can represent statistical data to spatial representation. This map showed the number of people injured and died. The towns of Bhachau and Anjar suffered a higher percentage (4.09% and 2.32% respectively) of death and injuries compared to other affected regions like Bhuj, Rapar, Gandhidham, and Ahmadabad in the Gujarat earthquake of 2001. The reason behind this higher percentage of death and injuries in Bhachau and Anjar is mainly due to their proximity to the epicenter of the earthquake, which was located near the village of Bhachau. The earthquake's intensity was much higher in these areas, and the buildings and infrastructure were not built to withstand such a severe quake. As a result, a significant number of buildings and structures collapsed, causing a higher number of fatalities and injuries. Furthermore, Bhachau and Anjar are small towns with a lesser population compared to the larger cities like Bhuj and Ahmadabad. This meant that the ratio of death and injuries to the population was much higher in these towns.

4.6 DAMAGES DISTRIBUTION MAP- 2001 GUJARAT

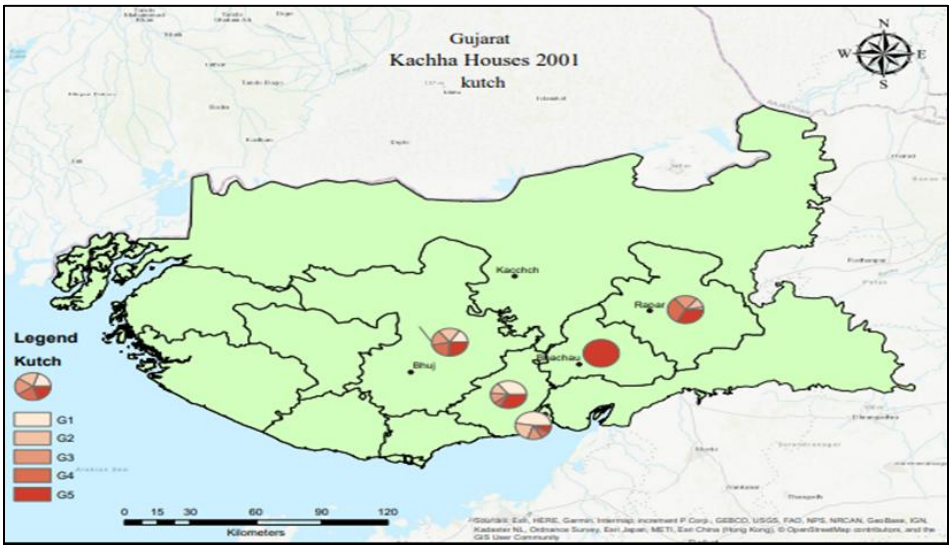


4.6.1 Pucca house and % damage in Kutch -2001



This map represents that how much intensity of damage occurred in a specific region, there are five categories of damage occurred with the pucca house. And through the spatial analysis, we can represent the data in a meaningful manner. (same with Kuchha house)

4.6.2 Kuccha house and % damage in Kutch -2001



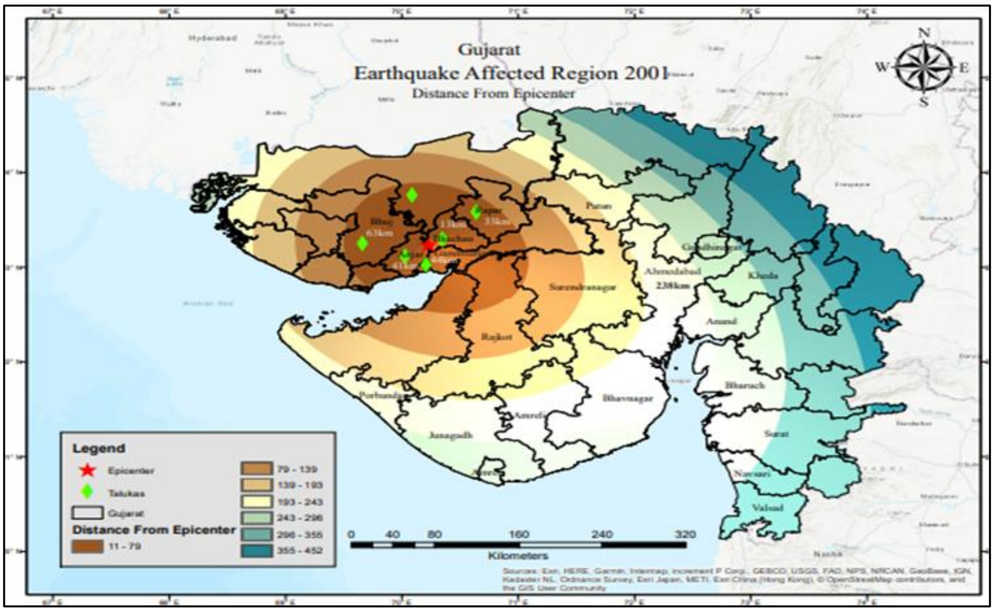
As the map shows, kutcha houses and huts were the most vulnerable to damage, with 85% and 90% of these buildings suffering total damage, respectively. Pucca houses, which are made of more durable materials, were also significantly affected, with 60% of them suffering total damage.

The percentage of buildings that suffered partial damage was higher for pucca houses than kutcha houses and huts, indicating that these buildings were more resilient. In terms of the geographic distribution of damage, Bhuj and Bhachau which were closer to the epicenter of the earthquake, suffered the most damage across all building typologies. Ahmadabad, which was further away, suffered the least amount of damage, particularly for pucca houses. The high percentage of total damage for kutcha houses and huts highlights the need for better building practices and materials in vulnerable areas.

4.7 Distance-Epicenter map

The epicenter map represents the total distance from the epicenter. District talukas distance from the origin of the earthquake.

Bhuj, being the closest town to the epicenter, experienced the highest intensity of the earthquake. The town had a population of around 345013 people at the time of the earthquake, and it suffered the highest number of casualties, with over 2500 deaths and many more injuries. The earthquake caused widespread damage to buildings in Bhuj, with almost all the buildings in the town either severely damaged or completely destroyed.



Rapar is another town in the Kutch district, located about 33 kilometers east of Bhuj. The town had a population of around 198000 people at the time of the earthquake and suffered significant damage. However, the intensity of the earthquake was higher in radar, and the percentage of death is lower relatively, with **0.37%** deaths and many more injuries.

Gandhidham is a larger town located about 44 kilometers west of Bhuj. The town had a population of around 201569 people at the time of the earthquake and experienced significant damage. However, the intensity of the earthquake was higher in Gandhidham compared to Bhuj and Rapar, and the number of casualties was relatively lower, with **0.67%** deaths and many more injuries.

Bhachau is another town located about 13 kilometers north of Bhuj. The town had a population of around 147891 people at the time of the earthquake and suffered significant damage. However, the intensity of the earthquake was very much higher in Bhachau compared to Bhuj, and the number of casualties was relatively higher, with **4.09%** deaths and many more injuries. The earthquake caused widespread damage to buildings in Bhachau, with almost all the buildings in the town either severely damaged or completely destroyed.

Anjar is a town located about 41 kilometers east of Bhuj. The town had a population of around 1,60,292 people at the time of the earthquake and suffered significant damage. The intensity of the earthquake was lower in Anjar compared to Bhuj, but the town still experienced a large number of casualties, with **2.32%** deaths and many more injuries

Ahmedabad is a major city located about more than 220 kilometers southeast of Bhuj. The city had a population of over 5 million people at the time of the earthquake, and it also experienced significant damage. However, the intensity of the earthquake was much lower in Ahmedabad compared to the towns in the Kutch district, and the number of casualties was relatively lower, with around 700 deaths and many more injuries.

In general, the closer a town was to the epicenter of the earthquake, the higher the intensity of the earthquake, and the more severe the damage and casualties. Additionally, the population density of a town played a significant role in the number of casualties and the extent of damage. The larger the population, the more people were exposed to the earthquake's effects, and the more buildings were at risk of damage. Finally, the building typology also played a role in the extent of damage. Buildings made of more resilient materials, such as concrete or steel, were more likely to withstand the earthquake's effects compared to buildings made of more brittle materials, such as adobe or unreinforced masonry.

CHAPTER-5 DAMAGE DETAILS IN DIFFERENT TOWNS

5.1 DAMAGE IN ANJAR

Anjar is a town that has experienced severe devastation three times in the past 184 years, with the most recent being in 2001 due to an earthquake. The earthquake that occurred on July 21, 1956, caused significant damage to property and resulted in the loss of over 100 lives. The town's old stone-in-mud buildings were completely destroyed, while newer brick and cement buildings showed better resistance. Reported magnitude and Intensity of this earthquake varies between 6-7 and VII–VIII respectively. The collapse of masonry structures was mainly due to out-of-plane wall failure, which was evident in the tragic incident of school children's deaths caused by falling walls in a narrow lane.

Figure 9: Anjar- stone in mud house

During the earthquake in Anjar, it was observed that the damage was localized, and a topographic rise running north-south through the city separated the area into two zones with different levels of damage. The eastern part of the city, at the low end of the rise, suffered relatively heavy damage, while the western part had light damage. Ground surveys confirmed that the north-south trending topographic rise was responsible for the difference in damage, with the heavy damage occurring below the rise and the light damage above it **Figure *9* 10.**

Figure 10*:* The aerial photograph of Anjar depicts extensive destruction on the left side of the image and comparatively minor damage on the right..

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Figure 11: A pigeon house, built with masonry in mud mortar, was standing amidst complete destruction despite being badly cracked.

Figure 12: depicts a new reinforced concrete building in Anjar, located north of the pigeon house shown in **Figure 11**. The building was badly damaged and partially collapsed. It appeared to have been designed with a central set of stairs, symmetrically dividing the building into two sections

Figure 12: Partial collapse of an apartment building Anjar

Figure 12 depicts a collapse of a soft/weak storey in Anjar where the front portion of the building gave way, while the back part remained intact, indicating inadequate reinforcement continuity. The height of the triangular front wall on the left was originally equivalent to that of the adjacent structure on the right

Figure 13: Destruction of masonry structures in the old section of Anjar

Figure 14: The buildings that demonstrated good performance in Anjar were situated in close proximity, about 2-3 blocks away, from the location where the photos in Figure 13 were captured.

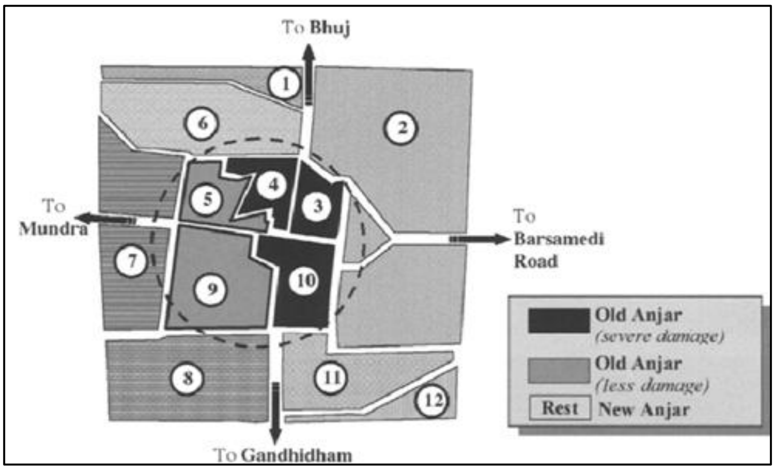

Figure 15: Anjar is divided into 12 wards, the most central of which sustained the most damage

The old town area of Anjar, consisting of wards 3, 4, 5, 9, and 10, was severely damaged during the 2001 earthquake due to the use of random rubble sandstone masonry in lime mortar without earthquake-resistant features. Ward 10, which was reclaimed from a pond, sustained almost complete collapse. Although wards 5 and 9 suffered less damage, they were still affected by the earthquake. No comprehensive repair and strengthening was undertaken after the 1956 earthquake, and structures that collapsed were rebuilt using the same construction methods. The new Anjar area, constructed mostly in the last decade, had similar configurations but used cement mortar instead of lime/mud mortar and had more common features like lintel bands in residential construction. The deficiencies in construction in Anjar resulted in total or near-total collapses of structures, as shown in Figure 16. Total or near total collapses of structures in this region suggest the following deficiencies:

- **Inadequate walls**

Stone masonry walls in lime mortar have weathered over time, making them weak. Re-used sandstone blocks may not bond well, and thick walls constructed in two layers are vulnerable to seismic activity. Tall walls without support performed poorly. However, some structures in Anjar with lateral force resisting elements, such as wooden post and lintel systems or inclined members, remained intact during earthquakes. (See **Figure 16** to **Figure 19** for visual examples.)

- **Inadequate roof-to-wall connection**

Wood runners were used room-wise (only covering the length of the room) because longer pieces were not available. This caused the floor systems of each room to behave independently during seismic activity and pull apart from one another **(**see **Figure 20**and **Figure 21).** Additionally, the failure of walls constructed in two layers led to roof collapses and numerous deaths.

Figure 16: Due to the lack of through-stones and the use of thick walls made of small rubble, the walls often split into two layers, which compromised their ability to bear gravity loads.

Figure 17: Lowering the height of the unsupported masonry panels in the tall gable walls could be a significant factor in the rebuilding process.

Figure 18: This building with post system survived in collapsed old Anjar

Figure 19: The inclined concrete stair slabs may have added lateral strength to weak masonry.

Figure 20: Damage or failure caused by interrupted runners over interior walls

Figure 21*:* Floor separation occurred during intense shaking.

5.2 DAMAGE IN BHACHAU

A town with a population of over 100,000 is called Bachhau. Gujarat state's Kutch district, which is located there, lost the majority of its housing infrastructure in the earthquake of 2001. The Gujarat government's post-earthquake housing damage study found that Bachhau had more than 13,000 structures, 10,000 of which were residences. This indicates that houses made up approximately 75% of the structures erected in Bachhau. Bachhau, however, lost approximately 90% of its housing stock, with more than 9,000 dwellings being completely demolished, half of which were squatter residences. 10% of the remaining properties were severely damaged and became uninhabitable.

The age of the structures and the subpar house construction were the main factors in the extent of the destruction. The majority of homes in Bachhau's official housing market were older than thirty to forty years and did badly after the earthquake. These homes were not designed and constructed of strong load-bearing masonry walls utilising cut stones, mud bricks, random stones, or burnt clay bricks with either mud or cement mortar (see Figure 23 below). Residents typically plastered cement plaster to the inner and exterior surfaces of the walls to reinforce them, unknowing of the weak core within, but the thick walls had a hollow core inside. Many homes were vertically expanded to add a second level as families expanded without fortifying the foundation.

Figure 22: structure that is not designed. Before the earthquake, burned clay bricks and mud mortar were often used to build walls in Bachhau homes.

Temple roofs in typical 5-10 meter high structures have ornate pyramid shapes and no reinforcement due to cultural beliefs about iron being inauspicious. However, the Bhuj earthquake caused many of these roofs to topple over (see **Figure 23**). As changing the architecture of these temples may not be allowed by customs, using different construction materials is recommended to improve their safety during seismic activity.

Figure 23: Destruction of a 5m tall temple at Bacchau

Figure 24: Aerial photo of near total devastation of village Bhachau

Figure 25: Damage to masonry construction due to inadequate connections between the walls

Figure 26: Damage to masonry construction due to inadequate connection between the walls

Figure 27: Collapse of this masonry structure was done to wall failure

Figure 28: In a few instances, such as this masonry structure, the roof alone was responsible for Structural collapse

The scale of damage in Bachau was unprecedented, with the entire town practically levelled. In a large reinforced concrete framed structure, a few columns had completely collapsed, leading to the failure of the slab. The beam column joints in all columns showed total crushing of concrete and hinge-like behavior, clearly indicating poor ductility. In the town, many stone-in-mud masonry buildings had completely failed, and a few two-story houses using columns, masonry walls, and lintel bands also suffered damage. As with Samakhyali, the portion above the lintel remained relatively intact, while some wall failures occurred on the ground floor. In one building, a large lateral sway was visible below the lintel band, indicating the "soft first storey" behavior.

Figure 29: Rigid box-like behaviour above lintel band (Bachau)

5.3 DAMAGE IN BHUJ

Bhuj, with a population of over 330,000, is located in the central region of Kutch district, as shown in figure 26. The city suffered extensive damage to both housing and infrastructure during the 2001 Gujarat earthquake. The damage survey conducted after the earthquake revealed that Bhuj had approximately 50,000 housing units before the disaster, out of which more than 13,000 completely collapsed and over 24,000 were damaged. This implies that around 75% of the houses in Bhuj were either destroyed or damaged due to the earthquake. As per the Census of India 2001, the population of Bhuj was 345,043.

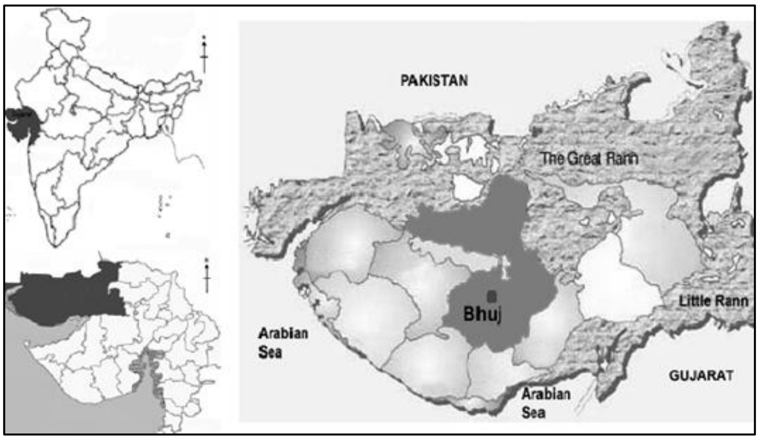

Figure 30: Bhuj location map. Maps on the left show location of Gujarat state of India (top left) and kutch district in Gujarat state(bottom left).(source: Maps Rewoked , Base maps from www.mapsof india.com)

The town of Bhuj has experienced the devastating effects of a significant earthquake. The old town, located inside the fort, suffered immense damage with most of its stone-in-mud constructed buildings of one to two storeys collapsing due to poorly bonded masonry. The palace buildings, which were taller, fared better, but an ornamental stone chattri was completely destroyed. In contrast, the newer parts of Bhuj, where most of the one or two storeyed buildings were constructed using brick or stone in cement mortar, sustained only minor cracking. However, multi-storeyed buildings with only columns in the basement fared poorly, and those with stiffening walls in the basement performed better. One three-storeyed stone masonry building with cement mortar joints suffered only minor cracks. Most of the elevated water tanks, with natural periods ranging from 1.0-3.0 Hz, were undamaged, although it is suggested that the ground motion may have had higher frequencies.

Some of the buildings built by the Central Public Works Department (CPWD) had earthquake-resistant features such as lintel bands and corner reinforcement. However, it has been studied that two such buildings behind the Bhuj railway station, which revealed that one building's wall below the lintel band suffered out-of-plane failure, while the lintel band collapsed. In the other building, despite the presence of corner reinforcement, the corners were badly fractured, and the stones came loose, highlighting the inadequacy of such measures when the ground motion is intense.

Figure 31: Most stone houses in the old town of Bhuj collapsed and Destruction in Bhuj

Figure 32: Damage to a rubble stone and mud mortar house in old Bhuj

Figure 33: Damage to cutstone and lime mortar masonry building in old bhuj

Figure 34: BHUJ: Stone in CM masonry building with minor damage

Figure 35: BHUJ: out of plane failure along with Lintel band failure.

Figure 36: BHUJ: RC column failure

Figure 37: BHUJ: corner failure in the presence of corner reinforcement

Figure 38: Soft storey collapse of a five storey apartment building in Bhuj

Figure 39: Soft storey collapse of a 5 storey apartment Building in bhuj

Figure 40: Typical soft storey collapse in Bhuj

A soft or weak storey can be created when a storey has significantly less lateral stiffness and/or strength compared to the floors above and below it. This is commonly observed at the ground floor when it is used for purposes such as parking, a shop front, or other similar activities. During a seismic event, most of the deformation demand is concentrated at this level, resulting in a large rotation demand in columns that have not been designed for ductility, Unfortunately, soft/weak storey collapses have occurred in several past earthquakes. **Figure 40** illustrates a typical collapse caused by a soft storey.


Figure 41: Overturned building in Bhuj


Figure 42: Building collapse in Bhuj

In **Figure 42**, a column failure is depicted, which occurred due to the reduction of its length leading to an increase in shear demand. This was caused by the presence of a non-structural wall, which created a fixity point. As a result, the stiffness of the column became higher than the others, causing it to attract a disproportionate amount of the load. This led to the column's capacity being exceeded, resulting in the failure that is visible in the figure. It is noted that this building may have experienced other types of failure as well.

Figure 43: Partly collapsed massive concrete framed building structure with infill brick masonry wall

Figure 44: Cut-stone building in bhuj

Figure 44 depicts an old government building constructed using solid cut stone masonry walls, which predates the 1900s. Despite being located in the centre of Bhuj, where many rubble buildings have completely collapsed, this building sustained only slight to moderate damage. The floors and roof are made of timber, and an adjacent building with similar cut-stone walls, which were at least 0.5m thick, also survived. However, the upper storey wall of the building in question suffered damage at the edges due to bending cracks caused by out-of-plane shear forces.. Additionally, untied architectural stonework has fallen off at roof level, as expected from severe shaking.

Figure 45: Collapsed open ground storey building in BHUJ

Figure 46: Damage to floor slabs and columns at the re-entrant corner of L-shaped building in bhuj

Figure 47: collapse of a partially open ground story building in bhuj , coupled with vertical split of the building at the midline

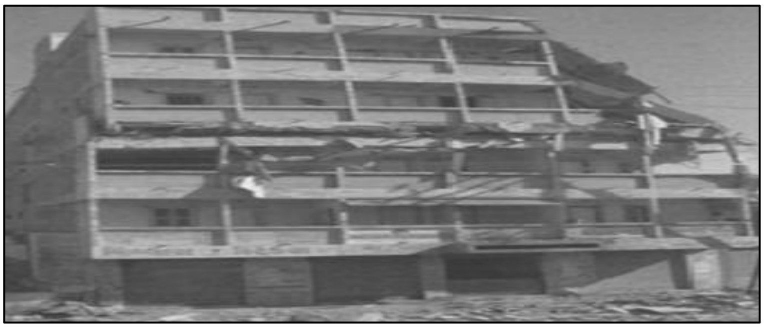

Figure 48: Intermediate story collapse in the 6 story building in Bhuj

5.4 DAMAGE IN GANDHIDHAM

Figure 49: Map showing Gandhidham and Adipur cities (Image courtesy Google maps)

Gandhidham and Adipur are located at latitudes 23°4'60’’N & longitude 70°7'60’’E and latitude 34°16'15’’N & longitude 74°29'20’’E, respectively, and are considered to be among the most seismically active regions in Gujarat. These areas are classified as seismic zone V, which is known to be extremely vulnerable to earthquakes and has experienced some of the most devastating earthquakes in history. The 2001 Bhuj earthquake severely impacted these cities, resulting in significant damage to numerous buildings and facilities, including several recently constructed structures. Most of the buildings in Gandhidham were built using older design standards or non-engineered design, with over 60% of them being masonry structures.

The effects of the earthquake on multi-storeyed buildings in the town were quite evident. For instance, the Sayaji Hotel had basement floor columns with their smaller dimension perpendicular to the earthquake motion. As a result, the building swayed laterally by approximately 60 cm, and the columns subsequently collapsed, causing the building to sink by roughly a meter.

In another case involving an unfinished building, the basement floor columns gave way, leading to the building collapsing by one floor. However, one or two-storeyed buildings did not experience significant damage, although they developed cracks, particularly in areas where there were frames and non-load bearing walls. In such cases, the frames and walls separated cleanly.

Figure 50: Gandhidham: Column failure – shaking in weaker direction

Figure 51: The collapsed ground floor of the children's hospital and research center in Gandhidham is a typical example of soft ground floor failure, as shown in the inset close-up view.

Figure 52: Manual demolition and removal of wreckage of damaged hospital building with mid-floor collapse in gandhidham. wreckage showing showng clear separation of concrete and steel.(RCC) and indicated the quality of material.

F**igure 53:** Image showing soft storey building collapse in Gandhidham, highlighting absence of structural intergrity.

Figure 54: Image showing collapsed apartment complex in Gujarat, due to lack of continuos reinforcement causing failure where in, columns failed to resist shear and moments due to poor detailing and materials, particularly at the top and bottom of the columns. The basement and first storey levels collapsed, and the columns punched through the slab after shearing off the beam-column connection.

Figure 55: combination of collapses in Gandhidham

The collapse of buildings during the Gujarat earthquake was often caused by a combination of factors. For instance, in **Figure 55**, A water tower, a soft storey and a bad layout led to the collapse of an apartment block in Gandhidham. The building was shaken by the lateral force resisting mechanism of the lift core as a result of the torsion, and the section of the structure linked to the core eventually broke because of a soft story. On the structure's left side that has fallen, the water tank is still there.

Figure 56: This area of Gandhidham has many row constructions where there is little to no space between adjoining buildings. In some cases, infills are only made in one of the two buildings at the interface. The building on the left had no infills in the upper stories, while the building on the right experienced a collapse at the ground story.

In older urban areas, it is a frequent sight to witness the construction of buildings without any space between them. In some cases, infill masonry is only added to the common wall of the first building constructed, as seen in **Figure 56**. This practice is a result of an agreement between the owner of the new building and the owner of the existing building, where the former pays the latter and they mutually share the infill wall of the existing building.

Figure 57*:* Incorrect attachment to RC elevator core walls in Gandhidham.

Figure 58: This Gandhidham apartment building collapsed due to plain irregularity, causing larger deformations in the upper stories of the left block. It was under construction during the earthquake1

Figure 59: collapse of a corner of an L-shaped building in Gandhidham was caused by the failure ofthe floor diaphragm at the re-entrant corner.

Figure 58 depicts the partial collapse of the upper two floors of the left block of a 4-story RC frame structure with brick infill that was under construction in Gandhidham at the time of the earthquake. Due to a design asymmetry caused by the absence of infill walls in the upper two stories of the left block, the flexible upper stories experienced greater earthquake deformations. This, together with the fact that there were non-ductile columns, caused the upper two levels to collapse. Similar to that, **Figure 59** depicts the partial collapse of a three-story commercial structure in Gandhidham that was situated on a corner lot. The earthquake caused one of its wings' ground stories to collapse and split apart.

5.5 THE AHMEDABAD EPISODE

Despite being 200 km away from the epicentre, many RC frame buildings in Ahmedabad suffered severe damages and collapses during the earthquake, highlighting the potential impact of side effects. Ahmedabad is located on thick alluvial deposits along the Sabarmati River, and collapsed buildings were dispersed throughout the city. Some of the collapses occurred in areas with poor soil conditions or non-engineered fills, while others were potentially influenced by changes in real estate development byelaws. The high peak horizontal ground acceleration (PGA) recorded at the Passport Office Building in Ahmedabad suggests that ground motion amplification may have occurred due to the alluvial deposits.

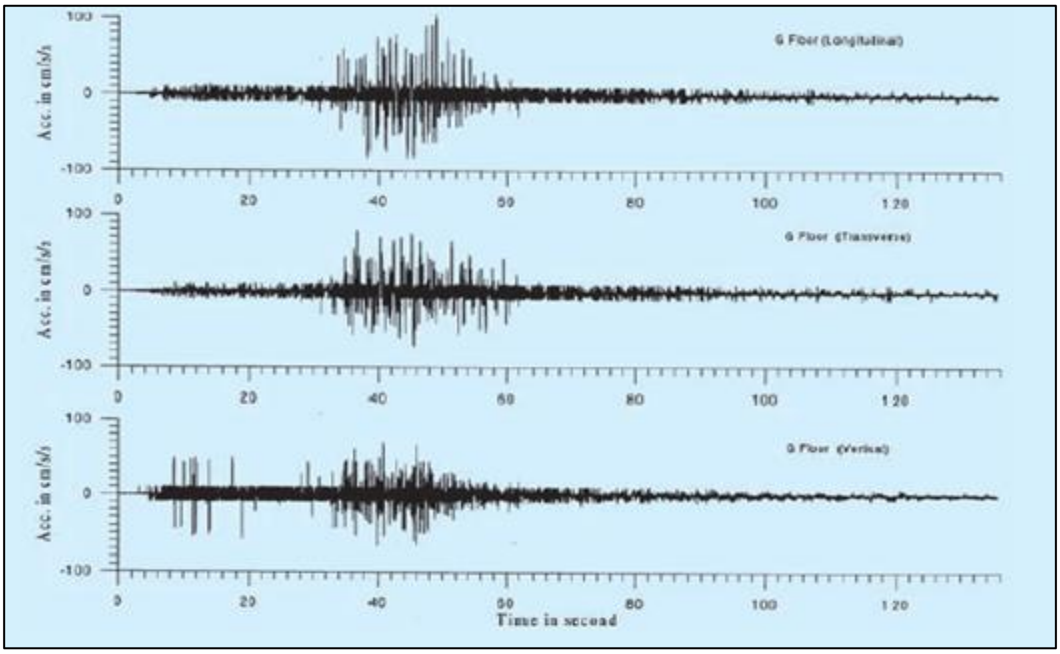

Figure 60: Accelerogram -recorded at the basement of building in downtown Ahmedabad

5.5.1 Building period versus Ground Motion Period

As earthquake shocks travel away from the source, short-period components of ground motion typically dissipate faster than long-period components. Ground motion at longer distances from the epicenter tends to have predominantly long-period components, which may explain why shorter buildings in Ahmedabad did not experience significant damage. However, buildings that collapsed during the earthquake were between ground plus four to ground plus ten-story heights and had elastic fundamental periods that likely overlapped with the predominant periods of the ground motion, estimated to be 0.5 seconds or longer. This near-resonant response may have contributed to much of the damage sustained, particularly considering the type of construction used for these buildings. The available ground motion record did not allow for precise determination of the predominant period.

5.5.2 Soft soil

A significant observation has been made regarding the soils underlying the collapsed buildings in Ahmedabad. While there appears to be no clear pattern in the location of collapsed buildings, a closer analysis reveals that most of them were located along the old path of the Sabarmati River. The collapsed buildings in areas west of the river were also found to be closely aligned with the old path.

In the south and southeast of the city, particularly in the Mani Nagar area where additional collapses were observed, the buildings were located between two lakes, suggesting the presence of poor soil conditions or non-engineered fills. While this evidence is compelling, further field testing would be necessary to confirm these conclusions.

5.5.3 Type of construction

Multistorey residential buildings in much of the world, including Ahmadabad, are constructed with reinforced concrete frames and unreinforced clay brick masonry infill. This poses a problem because while intact, the infill adds significant stiffness to the building, making it more susceptible to earthquake forces.

If the infill fails, the building's period lengthens suddenly, which can either reduce or increase the earthquake forces depending on the nature of the ground motion. Additionally, the bare frame must have the ability to resist the altered earthquake forces; otherwise, severe damage or collapse may occur.

5.5.4 Damages in Ahmedabad

Ahmadabad is a city with over 4.5 million people and more than 5000 multi-storeyed buildings. However, about 100 of these buildings have collapsed, causing over 1000 deaths. Interestingly, masonry buildings with only 1 or 2 storeys have largely escaped damage. One collapsed building, the SURABHI apartments (ground+ 4 storeys), was partially analysed and found to have a fundamental frequency of 1.31Hz.The city is located on a deep layer of silty sand that extends several thousand feet in depth, and some buildings have been constructed on filled-up soil in tank beds. It can be inferred that due to the great distance from the epicenter and the relatively soft soil, the ground motion frequency is expected to be low, and indeed the ground motion record shows a dominant frequency of about 1.0 Hz.

The masonry buildings of one to two storeys will rarely have frequencies below 5.0 Hz. Thus, the considerable separation between the natural frequencies and the ground frequencies ensured the safety. The frequency was low, essentially because of the ground basement floor consisting of columns with no walls in between. The conspiring of the factor to lead to failure of multi-storeyed buildings is now clear. The two points may now be highlighted:

- The wall free basement led to a lower natural frequency which was within the range of ground frequencies.
- The basement floor develops the largest lateral shears and the system of columns do not have the stiffness offered by the walls to resist the lateral load moments.

The collapse of multi-storey buildings can be attributed to two main reasons: firstly, the absence of ductile detailing in columns which results in a brittle crushing of concrete and subsequent collapse of columns; and secondly, the lack of wall-free basement design which leads to a lower natural frequency, falling within the range of ground frequencies. Other factors such as poor quality of concreting, inadequate reinforcement detailing, and foundation failure due to liquefaction or large overturning moments with inadequate footing areas in soft soils may also contribute to building collapse.

5.6 MANSI COMPLEX

Figure 61: The multistorey building (Mansi complex) in Ahmadabad soon after the earthquake, shown in both general and close-up views.

Figure 62*:* The 11-story building in front of Mansi Apartments, Ahmadabad collapsed due to a soft story.The presence of a swimming pool and reservoir at the top of the building added to the severity of the damage.
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Figure 63: This image provides a detailed look at the debris of Mansi complex, revealing the placement of reinforcement and the quality of concrete used in the collapsed columns.

Figure 64: This image shows the reinforcement details of a column that failed in a soft storey collapse. It is apparent that the longitudinal bars are heavily congested due to their lapping at one location, and there are insufficient lateral ties over the splice length

Figure 65: Collapse of flexible side of 11-story apartment building in Ahmedabad due to plan Irregularity

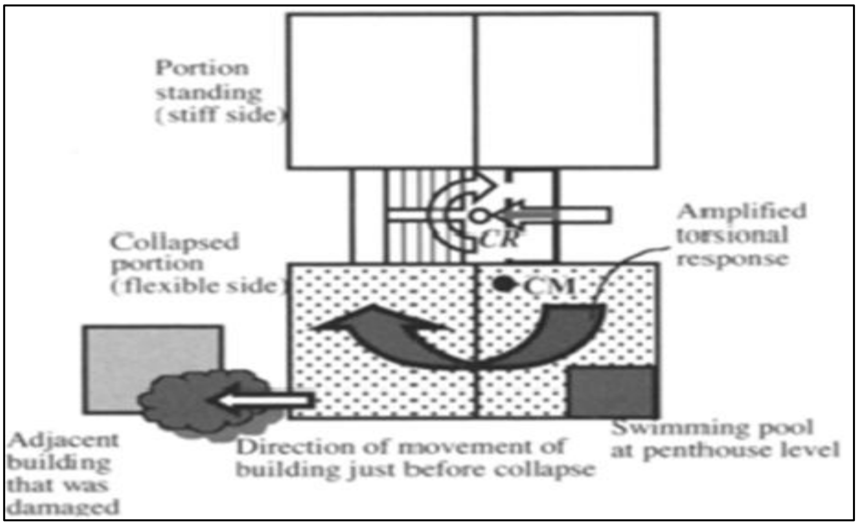

Figure 66: Damage and schematic representation of failure

The collapse of half of the 11-story apartment-cum-commercial building in Ahmadabad can be attributed to plan asymmetry, which left the stiff portion of the building standing (refer to **Figure 65**). The addition of a swimming pool at the roof level on one corner of the building resulted in excessive motions on the flexible side, causing significant deformations and shear demands on the columns.

It is unlikely that these columns had the capacity to withstand such large deformations, leading to their failure and subsequent loss of vertical load-carrying capacity. The flexible side of the building eventually collapsed, with its debris falling on an adjacent two-story building located approximately 10 meters away. This collapse suggests that the building exhibited amplified torsional behaviour.

Figure 67: Shikhar apartments, Ahmadabad .Building collapsed due to soft story effects

Figure 68: Column footing located approximately 2m below grade at Shikhar Apartments in Ahmedabad

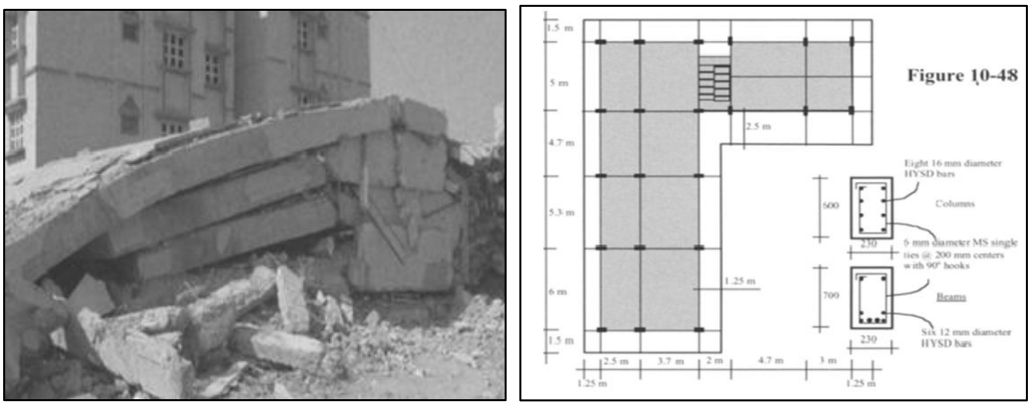

Figure 69: Collapsed of an L-shaped school building in Ahmadabad. Columns had no ductile detailing. Notice orientation of 230mm wide columns in long wing; small resistance to deformation in long direction.

The collapse of a 4-story L-shaped school building in Ahmadabad resulted in the tragic death of numerous children (Figures 62 and 63). The structural system of the building was weak-column strong-beam, and the columns were nonductile. These factors, along with the building's plan asymmetry, likely contributed to the collapse.

Figure 70: Ground floor column in Akshardeep apartment complex, Ahmadabad

Figure 71: Poor quality concrete and lack of seismic detailing evident in beam column connection

CHAPTER-6 REPAIR AND RETROFITTING OF STRUCTURES IN KACCHCH DISTRICT AND AHMADABAD DISTRICT

6.1 INTRODUCTION

The objective of this report section is to provide easy-to-follow design and structural recommendations that can enhance the strength of structures and minimize their vulnerability. Seismic design considerations should be implemented during construction to minimize earthquake damage. After an earthquake, certain techniques can be employed to strengthen buildings and prepare them for future events. Careful selection of building sites and materials is necessary to ensure technical requirements are met. When restoring damaged buildings through retrofitting, expert advice must be sought. Local authorities should pay close attention to such cases, as buildings that have lost their inherent strength may not survive future earthquakes, leading to complete collapse.

6.1.1 Seismic Strengthening (Retrofitting)

To enhance the seismic resistance of an existing building and make it safer during future earthquakes, several measures can be taken. These may include installing seismic bands, removing potential sources of weakness or areas with large mass and openings in walls, adding shear walls or strong columns to the structure, bracing roofs and floors to act as horizontal diaphragms, ensuring proper connections between roofs and walls, and reinforcing the connections between walls and foundations. These upgrades aim to improve the building's ability to withstand seismic forces and minimize damage during earthquakes.

6.1.2 Cost of Seismic Protection

Research indicates that it is more cost-effective to design a building with earthquake resistance measures from the outset rather than carrying out repairs and strengthening works later on. The additional cost of designing and implementing seismic features in a building is estimated to be approximately 10% more than a non-engineered building.

However, repairs for a building lacking seismic features may cost 2 to 3 times more than the initial expense of introducing such features. In cases where repairs and strengthening are necessary, the costs could escalate to 4 to 8 times the original expense (Arya, 2000).

6.2 SHORT TERM RETROFITTING

In response to the fear and panic caused by the earthquake, local engineers and builders began taking steps to strengthen buildings and prevent collapse during aftershocks. The immediate priority was to restore the confidence of residents by ensuring the safety of buildings. The Gujarat Institute of Civil Engineers and Architects (GICEA) in Ahmedabad released a guide on repairing and strengthening buildings soon after the earthquake. The seismic vulnerability of open ground story buildings, which had been overlooked by professionals and laypersons in India for many years, became apparent after witnessing the collapses in Ahmedabad. Therefore, the focus was on strengthening ground story columns through jacketing, although this approach had limitations. Several quick retrofit measures were implemented on multi-storey buildings, but these still required further improvements.

During earthquakes, buildings undergo movements in multiple directions, and it is not cost-effective to design them for all possible forces. However, it is crucial to address horizontal movement, which is a major cause of building damage during earthquakes. Structural components such as shear walls, slabs, columns, and beams should be properly braced or tied together so that they can function as a cohesive system. Failure of any one of these components can result in severe damage or even complete collapse of the building. The common types of damage observed in all buildings are summarized below.

6.2.1 Damages in Masonry walls

The majority of buildings utilize burnt bricks as masonry infill in reinforced concrete framed structures. However, in some instances, such as in the construction of the Police headquarters, hollow concrete blocks have been utilized as infill materials. Despite this variation in materials used for infill, all of these walls have been observed to be disconnected from the concrete frame. This lack of connection causes the columns and walls to shake differently, leading to cracks and failures. As depicted in **Figure 73** new constructions are being built without any tie beams or rods between the walls and columns, exacerbating this issue.

Figure 72: Unreinforced Masonry infill's

Figure 73: Damages in Unreinforced Masonry infill's

Figure *72* illustrates the type of damage that can occur in masonry walls when there are no tie beams present. To address this issue, **Figure 74** provides possible reinforcement and retrofitting measures for masonry walls. **Figure 74 A** suggests the implementation of continuous horizontal reinforcement at lintel and sill levels, as well as on all sides of openings, along with vertical reinforcement at every 4-feet interval. On the other hand **Figure 74 B** displays the potential retrofitting measures that can be employed to repair the cracks in the masonry walls, as seen in **Figure 73**. It is crucial that these reinforcements are connected appropriately to the structural members to ensure proper reinforcement.

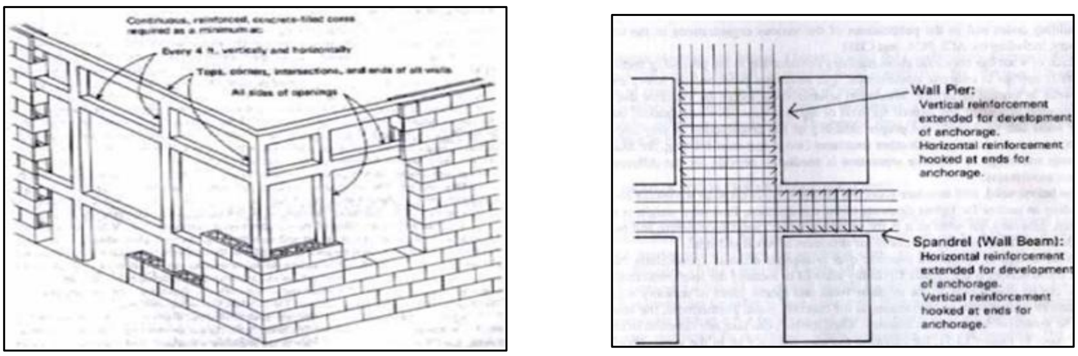

Figure 74: Details of Bracing for Masonry Walls A & B

6.2.2 Damages in Structural system

Columns and beams play a critical role in determining the strength of a building. Inadequate planning or design of these structural elements can significantly increase the likelihood of failure. **Figure 76** depicts various types of damages that can occur in columns. Typically, column failure can occur when the reinforcements lack the required size and number of rods, when the vertical reinforcement is not appropriately tied with the tie rods at regular intervals, when there is insufficient overlap between vertical bars, when the concrete thickness around the reinforcement is inadequate, or when the concrete quality is poor. These factors are the primary reasons behind column failure in buildings.

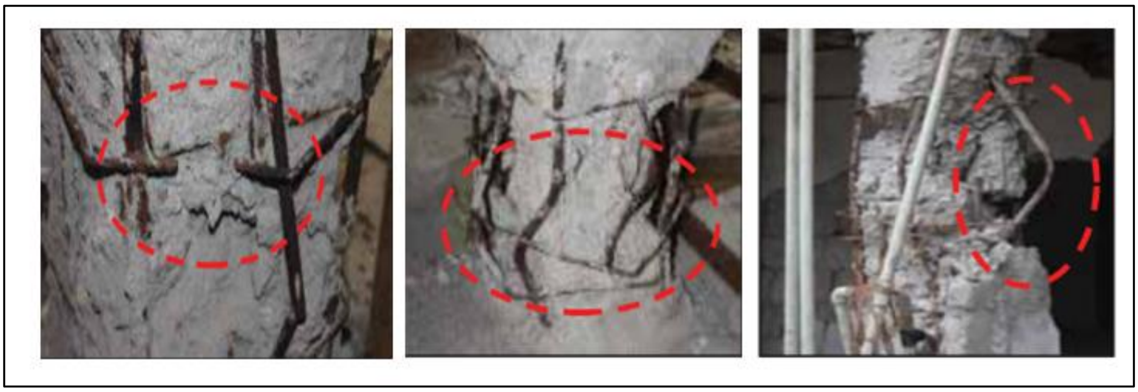

Figure 75: Reinforcement failures

Proper connection between columns, beams, and slabs is crucial for ensuring the stability of a building. **Figure 76** highlights the consequences of poor connections between columns and beams, as well as columns and slabs. In addition, it is important to ensure a symmetrical arrangement of columns to maintain the structural stability of the building.

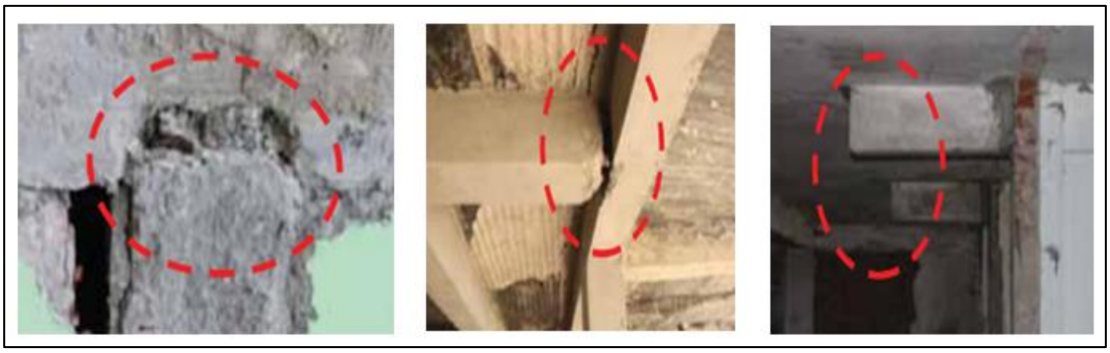

Figure 76: Connection between Structural Systems

Columns bear the building load and beams transfer slab load to columns. Shear walls limit horizontal shaking of columns during earthquakes.

Shear walls carry some weight from the slabs and beams, reducing the load on the columns and controlling horizontal motion. In the absence of shear walls, there is a higher risk of column failure. Therefore, it is crucial to ensure that shear walls are continuous between columns with minimal opening sizes. **Figure 77** depicts the absence of shear walls in buildings

Figure 77: Absence of shear walls

In cases where shear walls cannot be installed, or where columns have suffered damage in earthquakes, the use of braces is a recommended option. Vertical bracing is accomplished through the use of steel bars that connect columns, transfer the load, and control horizontal movement in columns. **Figure 78** provides several examples of vertical bracing.

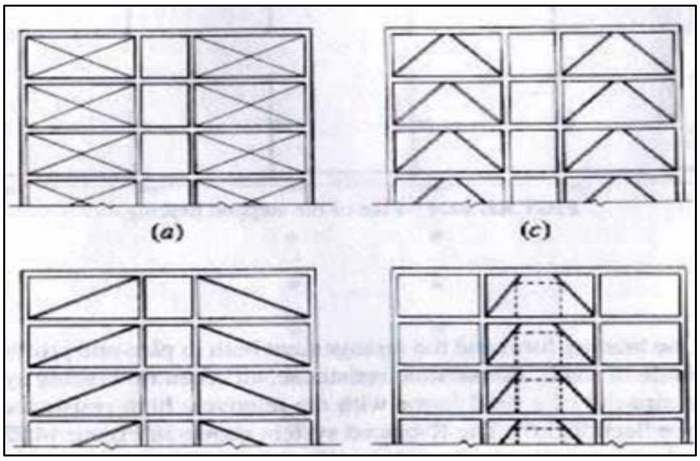

Figure 78: Vertical Bracing Systems

6.3 Retrofit strategies

Various retrofit stratigies have been adopted in Ahmedabad and other areas of the State of Gujarat, including:

1. Repairing broken infill walls and columns with points and new plaster (Figure 80).

2. Replacing every infill wall in the RC frame panels (Figure 81).

3. The open ground story's RC columns in the jacketing (Figures 83 and 84). In many instances of column jacketing, the plaster on the existing concrete column surface was left in place, and the additional reinforcement was not secured into the building frame or foundation.

4. Supporting beams with built-up sections, steel joists, or masonry pillars (Figure 85).

5. Steel bracing in open bays are provided (See Figure 86).

6. The perimeter floating columns are supported by masonry columns, steel joists, or masonry walls in the retrofit approach for propping cantilever beams.(Figure 86).

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Figure 79: In the affected area, many buildings experienced frame-infill separation, which was fixed by cleaning and filling the gaps with rich cement mortar. The accompanying photo displays an example of this type of repair at a school building in Gandhidham

Figure 80*:* At a two-story school building in Ahmedabad, the large block sandstone masonry infills in cement mortar were replaced entirely with burnt-clay brick masonry infills in cement mortar.

Figure 81: A partial collapse of the burnt-clay brick masonry infill held together with cement mortar occurred in the upper story of a three-story telephone exchange building in Bhuj. The solution to this problem involved replacing the infills in the entire building with lightweight foam concrete panels. The new panels were placed between asbestos sheets and secured to the building's frame using thin steel straps, including those at the lower stories

Figure 82: The ground level column of a seven-story old age home in Gandhidham was reinforced with a jacket, which covered it from the floor level to just below the top beams. In the visual, the column bars can be observed being curtailed on the side of the beam.

Figure 83: Hot-rolled I-sections were used to jacket the circular RC columns on the ground story of an 11-story commercial building in Ahmadabad. However, no connections were made between the steel I-sections and the concrete columns.

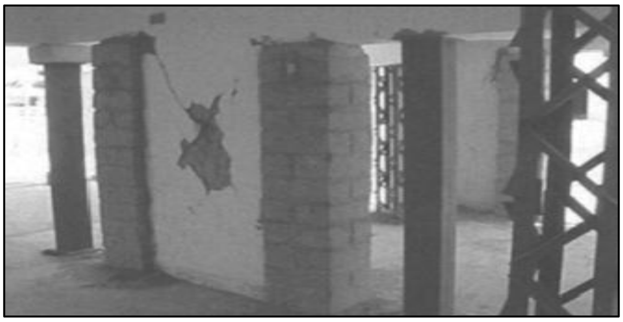

Figure 84: In a three-story residential reinforced concrete (RC) frame building located in Gandhidham, the RC columns are connected to brick masonry columns from the floor level up to the beam soffit. The beams are supported at intermediate locations with hot-rolled I- sections.

Figure 85: To reinforce open ground story panels, steel braces are used in specific cases. In this residential building, burnt clay brick masonry infill’s were used to fill in the gaps, and steel sections were wedged at the outer faces. Additionally, steel hollow box sections with a size of 100 and a plate thickness of 8mm were used as bracing members.

Figure 86: Reinforced concrete (RC) frame buildings that feature open ground stories typically have overhanging beams along the perimeter of the ground level. During the earthquake, many of these cantilevered beams experienced shear cracks. To retrofit this building, masonry columns were constructed underneath the tips of these beams.

Figure 87: To reinforce this reinforced concrete (RC) frame building with an open ground story, masonry infills were strategically placed in certain panels of the ground level. This was done without impeding parking in the open ground story.

6.4 JACKETING COLUMNS

The most adopted measure to strengthen RC columns in the ground story is through jacketing. This involves adding additional concrete and reinforcement around the existing column, as shown in **Figure 89.** Alternatively, steel angles and flats can be used to strap the old column before concreting, as depicted in **Figure 90**. In a building in Ahmadabad, after the earthquake, the ground story columns were jacketed to an unusually large size, as seen in **Figure 89**. However, in many cases, the jacketing has been done without removing plaster or roughening the surface of the old column. Jacketing usually begins at the finished ground floor level, rather than the foundation, although in some instances, it has started from the foundation, as illustrated in Figure82. Unfortunately, the longitudinal bars added to the additional concrete portion are often left projecting out without any connection to the older RC beam and column members above, as shown in Figure 83.

6.4.1 Exemplary Retrofit

A building consisting of a reinforced concrete frame with infills in the upper stories and an open ground story had experienced shear damage to the ground story columns and nominal frame-infill separation in the upper stories. In response, the individual apartment owners joined forces to undertake a formal retrofit program, which involved the following steps:

1. Cracks in the columns were filled with epoxy.
2. Gunite was applied to the cracked column faces.
3. Individual footings were rebuilt by modifying the existing 1.2m x 1.2m tapered footings to 1.8 m x 1.8 m x 0.6 m thick rectangular footings.
4. Tie beams were added between columns at the top of the modified footings.
5. Masonry walls were added over the tie beams in selected bays of the openground story panels.
6. Masonry walls were added under the cantilever beams that supported thefloating columns in the ground story.

This retrofit program required 1,800 bags of cement and approximately 11metric tons of reinforcing steel.

Figure 88*:* Before jacketing, mild steel angles measuring 75mm at four corners and 25mm steel flats were used as primary reinforcement for damaged RC columns in an open ground story building.

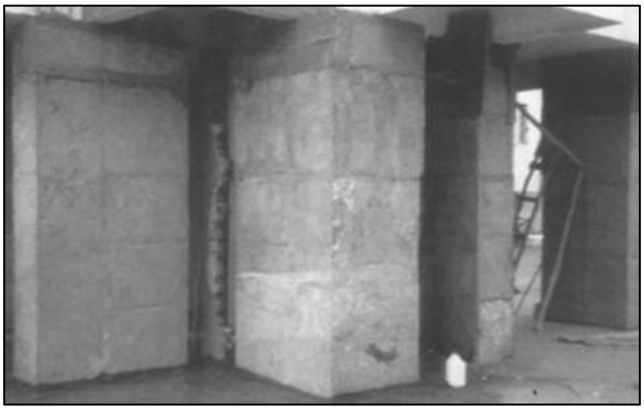

Figure 89: The original purpose of open ground stories in RC frame buildings was for parking, but after reinforcing the columns with jackets, the available space for cars was limited due to increased column size, leading to a disruption of the intended parking function.

Figure 90: Shows that there were only a few cases where column jacketing began at the footing level. However, even in those instances, it is uncertain whether the column reinforcement was anchored into the footing or if the footing itself was strengthened.

6.5 HOUSING RECONSTRUCTION

The Bhuj earthquake of 2001 was a devastating disaster that resulted in significant loss of life and property in the region. Following the earthquake, the Government of India launched several schemes and initiatives to aid in the reconstruction and rehabilitation of affected areas. These schemes focused on providing financial assistance and technical expertise to individuals and organizations involved in the reconstruction process.

One of the key initiatives undertaken in the aftermath of the earthquake was the Gujarat Housing Board (GHB) scheme, which aimed to provide affordable housing to the affected population. Under this scheme, several housing colonies were constructed in the Bhuj region, including the Madhav Residency, Shakti Nagar, and Om Residency. These colonies were built using earthquake-resistant technology and provided housing to thousands of families affected by the earthquake.

Another significant initiative was the Indira Awaas Yojana (IAY), which aimed to provide financial assistance to individuals for the construction of their homes. The scheme provided financial assistance of up to INR 70,000 for the construction of a new house or the repair of an existing one. Under this scheme, thousands of homes were reconstructed or repaired in the Bhuj region.

In addition to these initiatives, several NGOs and private organizations also played a significant role in the reconstruction process. For example, the Aga Khan Development Network (AKDN) launched the Earthquake Rehabilitation and Reconstruction Program (ERRP), which focused on the reconstruction of traditional Kutchi houses using earthquake-resistant technology. Through this program, several thousand houses were retrofitted or reconstructed in the Bhuj region.

Overall, the reconstruction efforts in the aftermath of the Bhuj earthquake were significant, with thousands of homes being constructed, repaired, or retrofitted using earthquake-resistant technology. While much still needs to be done to fully rehabilitate the affected population, these initiatives provide a strong foundation for ongoing efforts to build a safer and more resilient community in the region.


BARBER
TOWN


XEROX

CHAPTER-7 CONCLUSIONS AND FUTURE SCOPE OF STUDY

Based on the given information, a 7.7 moment magnitude earthquake created damages - mainly in six different Talukas/Districts in Gujarat, namely Anjar, Bhuj, Rapar, Bhachau, Gandhidham, and Ahmadabad. The intensity of the earthquake varied from VII to X on the Modified Mercalli Intensity (MMI) scale. The earthquake's epicentral distance ranged from 13km to 238km, and the peak ground acceleration (PGA) varied from 0.15g to 1.84g. The soil/site condition varied from clay and loam to alluvial and clayley, which could affect the seismic waves' propagation and amplification **(Table11).**

Table 11: Summary Table

LOCATION	ANJAR	BHUJ	RAPAR	BHACHAU	GANDHIDHAM	AHMEDABAD
Magnitude and Intensity	7.7 &IX	7.7&IX	7.7&IX	7.7 & X	7.7 &IX	7.7 &VII
Soil/Site	Clay and loam	Alluvial and clayey	Sandy and loamy	Sandy and loamy	Sandy and clayey	Alluvial and clayey
Epicentral distance (km)	41Km	63Km	33Km	13Km	44Km	238Km
PGA(g)	1.54	1.82	1.51	1.84	1.44	0.15
Population density	high	moderate	moderate	low	high	high
Deaths and injuries	high/high	high/high	High/moderate	Hig h/high	Moderate/Moderate	Moderate/high
Dominant building typology	URM	URM	URM	URM	RC	RC
% damage	80%	90%	80%	95%	70%	20%
Reasons						

The population density was high in Anjar, Gandhidham, and Ahmadabad, while it was moderate in Bhuj and Rapar and low in Bhachau. The dominant building typology was unreinforced masonry (URM) or kutcha houses and huts in all locations, except for Gandhidham and Ahmadabad, where reinforced concrete (RC) or pucca houses was dominant.

The earthquake caused high to moderate deaths and injuries, with the highest impact observed in Bhachau, Bhuj, and Anjar. The damage percentages varied from 20% in Ahmadabad to 95% in Bhachau, indicating significant destruction of buildings and infrastructure. The results suggest that the earthquake's impact was more severe in areas with a high population density and URM buildings (kutcha houses).

Conclusion 1

In conclusion, the 7.7 magnitude earthquake in India caused significant damage and loss of life, particularly in areas with high population density and URM or kutcha buildings. The variation in soil/site conditions, epicentral distance, and PGA also influenced the earthquake's impact. The results highlight the importance of earthquake-resistant construction and preparedness measures to mitigate the impact of future earthquakes. Designing and constructing earthquake-resistant buildings is crucial to minimize the damage caused by seismic activity. Reinforced concrete frame buildings, especially those with open ground stories, require better seismic design and detailing to improve their lateral strength and ductility. Incorporating ductile detailing, utilizing the stiffness and strength of brick masonry infills, and avoiding irregular structural configurations can also enhance seismic performance. By implementing these measures, we can build safer and more resilient structures that can withstand strong seismic effects.

The inadequate construction of roofs and walls, as well as insufficient investigation of foundations, are major factors contributing to damages in masonry structures during earthquakes. Deficiencies in roofing systems include heavy roofs, A-frame roof trusses without bottom tie members, and gable roofs without proper tie bracing. Wall systems also show deficiencies such as inadequate connection between walls, lack of positive connection between walls and roof, and oversized openings located at undesirable locations. Furthermore, construction practices often involve building one wall at a time, which takes away the basic essence of making an earthquake-resistant house. These deficiencies violate the requirements of buildings in Seismic Zones IV and V as per the Indian Standard guidelines. Therefore, it is not surprising that a large number of fatalities occur from building/dwelling collapses during earthquakes.

Conclusion 2 - Anjar town

Anjar town was one of the towns that suffered the most damage during the earthquake, despite being far from the epicenter. The reason for this was the soil amplification due to alluvial deposits, which made the ground in the town more vulnerable to the effects of the earthquake. The 1956 earthquake had already caused significant damage in Anjar, but the people did not learned the lesson and failed to take adequate measures to prevent similar damage in the future.

As a result, when the 2001 earthquake struck, Anjar once again suffered significant damage and loss of life. In contrast, the people of Bhuj town, which was closer to the epicenter of the earthquake, had learned their lesson from the past earthquakes in the region. They had implemented earthquake-resistant building requirements, which helped to reduce the damage and loss of life in the town. The earthquake-resistant building requirements in Bhuj included the use of seismic-resistant materials, reinforcement of building structures, and compliance with building codes and standards. These measures helped to minimize the damage caused by the earthquake and ensured that buildings remained standing, despite the strong tremors. Given the lessons learned from the Bhuj earthquake, it is clear that Anjar town is not suitable for future reconstruction or development without implementing similar earthquake-resistant building requirements. Without such measures, the town will continue to be vulnerable to earthquakes and suffer significant damage and loss of life in the future.

In conclusion, the Bhuj earthquake of 2001 serves as a poignant reminder of the importance of implementing earthquake-resistant building requirements in earthquake-prone regions. The people of Bhuj learned the lesson from past earthquakes and took appropriate measures to protect themselves. Anjar town, on the other hand, did not learn their lesson and suffered the consequences.

To prevent future disasters, it is essential to implement earthquake-resistant building requirements in vulnerable regions and ensure that people are aware of the risks and how to mitigate them and It is crucial to consider local factors such as soil type, seismic activity, and population density when designing and constructing buildings in earthquake-prone areas like Anjar. By taking these factors into account, it is possible to mitigate the risks associated with earthquakes and ensure the safety of the residents

Conclusion 3 - Ahmedabad city

The damage in Ahmedabad was primarily due to the poor quality of construction and lack of adherence to building codes, as well as the geotechnical aspects of the site, such as the use of substandard materials, soft soil, and the risk of liquefaction. These factors combined to make Ahmedabad more vulnerable to damage from the earthquake, despite being far from the epicentre. The high number of deaths and injuries underscores the importance of proper construction practices and building codes in earthquake-prone areas. In addition, the soil in Ahmedabad is predominantly composed of clay and alluvial deposits, which can amplify ground motion during an earthquake. This means that the seismic waves that reached Ahmedabad were amplified, causing more damage to buildings and infrastructure. The structural configuration and building typology of Ahmedabad also contributed to the extent of damage such as soft storey. Many of the buildings in Ahmedabad were constructed with poor quality materials and techniques, and were not designed to withstand earthquakes. This made them more vulnerable to damage and collapse during the earthquake. In contrast, other talukas in the Kutch district that was closer to the epicentre of the earthquake, such as Bhuj and Anjar, experienced more severe damage due to the higher intensity of ground motion. However, the soil in these areas is composed of more stable rock formations, which helped to mitigate some of the damage caused by the earthquakes.

7.1 Future scope of the study

Developing damage functions and vulnerability functions for different building typologies based on past earthquakes in the Indian peninsula, such as Bhuj, Jabalpur, Latur, and Koyna, is a crucial step towards improving seismic risk assessment and mitigation strategies. However, this is an on-going process, and there is a vast scope for future research in this area.One of the essential aspects of developing damage functions and vulnerability functions is to collect accurate and comprehensive data on past earthquakes. Therefore, future studies can focus on expanding the database of historical earthquakes in the Indian peninsula, including smaller and less severe earthquakes that may not have been adequately documented. This can provide a more comprehensive understanding of the seismic activity in the region and help develop more accurate and reliable models for seismic risk assessment.

Furthermore, future studies can also explore the impact of building design and construction practices on the damage and vulnerability of buildings during earthquakes. This can help identify the most effective design and construction practices for different building typologies, such as low-rise residential buildings, high-rise buildings, and commercial buildings.

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