सत्यमेव जयते

Compendium of Traditional Earthquake Resilient Construction

September 2023

NATIONAL DISASTER MANAGEMENT AUTHORITY (NDMA)
Government of India
NDMA Bhawan, A-1, Safdarjung Enclave,
New Delhi-110 029

Compendium of Traditional Earthquake Resilient Construction for Knowledge Sharing and Disaster Risk Reduction

Project Report

Submitted by:

Indian Institute of Technology
Roorkee

Indian Institute of Technology
Ropar

Assam Engineering College
Guwahati

Submitted to:

National Disaster Management Authority, New Delhi, India

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NATIONAL DISASTER MANAGEMENT AUTHORITY

PREFACE

Traditional building is a response to social and physical necessities that enable mankind to build structures that are climate-responsive. Such traditional buildings have seemingly been forgotten in modern era but they are regaining popularity, as the effectiveness of these traditional technologies has been clearly brought out during recent disasters. However, in many cases some traditional constructions have proven inadequate to resist strong earthquakes. Strong earthquakes are indeed extraordinarily disruptive events, but they also have large return periods, making it difficult to learn from them in short time spans. The entire Himalayan belt as well as the north-eastern region of India is susceptible and vulnerable to strong earthquakes. Hence the objective to identify and document the traditional building construction practices and suggesting safety measures for vulnerable building typologies has been clearly brought out in this report.

The safety measures recommended in this document are intended to further improve the earthquake resilience of the identified traditional buildings. It is hoped that the content presented in this report will prove to be helpful to the government organizations for the dissemination of traditional knowledge of earthquake-resilient building constructions and also to the concerned house owners to construct traditional buildings that are detailed to offer earthquake-resilience and subsequently reduce earthquake risk in the Indian Himalayan region. To facilitate easy understanding by the general public, the report highlights safety measures through self-explanatory sketches.

We take this opportunity to express our heartfelt appreciation to the team of experts from IIT Ropar, IIT Roorkee, Assam Engineering College and various stakeholders who extended their willing support, cooperation and commitment by devoting their expertise to make valuable contribution for the development of this document. We are optimistic that this effort will go a long way in enhancing the preparedness of the country to mitigate the effect of earthquake hazard.

Sh. Kamal Kishore
Member Secretary
In-charge

Krishna S. Vatsa
Sh. Krishna S. Vatsa
Member

Sh. Rajendra Singh
Member

Lt. Gen. Syed Ata Hasnain (Retd.)
Member

FOREWORD

The Indian Himalayan region is highly vulnerable to earthquakes and has been devastated by many strong earthquakes in the past centuries. Accordingly, this region falls under the two of the most severe seismic zones in the India's latest seismic zonation map. The historical evidence shows that this region has suffered significant damage to buildings and infrastructures during past earthquakes, adversely affecting lives, livelihood, and property. As a human response to earthquake disaster, the region has developed a local culture for seismic resistant building construction. Several post-earthquake damage surveys and reports suggest the superior performance of the traditional (indigenous) building types that evolved and existed in the region. Therefore, it is crucial to understand and document the traditional earthquake-resilient construction practices and promote them to achieve sustainable development and earthquake risk reduction goals.

With collaborative efforts of the Indian Institute of Technology Ropar, Rupnagar, Indian Institute of Technology Roorkee, Roorkee, and Assam Engineering College, Guwahati, and financial and administrative support from the National Disaster Management Authority, New Delhi, extensive field surveys have been conducted in the states of Himachal Pradesh, Uttarakhand, Meghalaya, Sikkim, Assam and also union territory of Jammu and Kashmir, and Ladakh to identify and document the existing traditional buildings. Six different traditional building systems are identified from the field surveys. These traditional building systems include Kath-kunni (Koti-banal) buildings in Himachal Pradesh and Uttarakhand, Thathara buildings in Himachal Pradesh, Rammed earth buildings in Himachal Pradesh and Ladakh, Dhajji-Dewari and Taq buildings in Jammu and Kashmir, and Assam-type Buildings in the states of Assam, Meghalaya, and Sikkim. This document intends to highlight both earthquake resilient and vulnerable features of the traditional buildings. The document also suggests and provides details of the strengthening measures for existing and new traditional buildings based on the observed vulnerabilities in them.

It is hoped that this document will help the national and state disaster management authorities, NGOs and Civil societies to promote and adopt the seismic resilient practices in local construction using locally available materials. The policy of using local materials by local artisans will also lead to livelihood support and a positive environmental impact.

Rajeev Ahuja
Professor andd Director
Indian Institute of Technology Ropar

AUTHORS’ MESSAGE

The authors are glad to share the compendium of earthquake-resilient traditional buildings, with an objective to document, disseminate, improve, and promote the traditional construction practices. This compendium is expected to help in promoting the good features of traditional construction practices and incorporate them in the future constructions to make them safer. The implementation of suggested strengthening measures in traditional buildings will also enhance the sense of security among the citizens and help in minimizing the loss of life and property.

The Himalayan region, in India, is home to many traditional buildings that have existed for centuries. Many of these traditional buildings have proven records of earthquake resilience, evidenced during past earthquakes. Modernization in the past few decades and the unavailability of traditional construction materials, viz. timber and stone, has led to a paradigm shift in building construction practices in these regions. This shift in construction practices poses a risk of extinction of the safe traditional construction practices and the wealth of knowledge embodied in these. However, it has been clarified that not all the features of traditional construction practices contribute to earthquake safety. Some suggestions on improvement/modifications in these features have also been included in the compendium.

With the financial and administrative support from National Disaster Management Authority (NDMA), New Delhi, in this report the traditional buildings existing in northern and northeastern states of India are identified and documented in terms of their siting, architectural and structural features. In addition, suitable seismic safety measures for strengthening the vulnerable features of existing traditional buildings and constructing new traditional buildings are also discussed with the help of self-explanatory sketches.

It is hoped that the developed document will help to promote and disseminate the knowledge on traditional earthquake-resilient buildings. In addition, the self-explanatory sketches related to seismic safety measures of existing and new traditional buildings and recommendations will help in achieving sustainable development and earthquake risk reduction goals.

Mitesh

Dr. Mitesh Surana
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology Ropar

Dr. Putul Haldar
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology Ropar

Dr. Yogendra Singh
Professor
Department of Earthquake Engineering
Indian Institute of Technology Roorkee

Dr. Jayanta Pathak
Professor
Department of Civil Engineering
Assam Engineering College Guwahati

EXECUTIVE SUMMARY

India's northern and northeastern states are prone to earthquakes and are mapped into the two most severe seismic zones IV and V, according to the latest Indian seismic zoning map. These regions are home to many traditional buildings that have existed for centuries. Many of these traditional buildings have proven records of earthquake resilience, evidenced during past earthquakes. Modernization in the past few decades and the unavailability of timber due to the ban on tree cutting by the forest department and subsequent strict government norms led to a paradigm shift in building construction practices in these regions. National Disaster Management Authority (NDMA), New Delhi, tried identifying and documenting the traditional buildings existing in India's northern and northeastern states. This project aims to identify and understand traditional building construction practices of the northern and northeastern states and their associated essential siting, architectural, and structural features imparting earthquake resilience to them. It also focuses on identifying the earthquake-vulnerable features in traditional buildings and suggesting suitable safety measures for strengthening them using state-of-the-art methods available in the literature to safely protect the inhabitants from earthquakes and promote traditional building construction.

The project team has conducted extensive field surveys to identify traditional buildings of the study region in detail. Six different traditional building typologies have been identified in the study region. These traditional building typologies are Kath-Kunni, Thathara, Dhajji-Dewari, Taq, Assam type, and Rammed earth. The critical aspects of these traditional building types that were noted down during the field surveys are siting conditions (location of the building site and topography), architectural aspects of the building (building plan shape, plan aspect ratio, size, number of stories, story heights, locations and placement of openings, etc.), structural features (wall/frame system, floor system, roof system, and their connections), the type of foundation used, the general health (visual conditions) of the building, contemporary modifications (if any), and materials that are used for construction. In addition, structural identifiers are given to each building system based on their structural attributes which aid in classifying traditional buildings.

A qualitative seismic vulnerability analysis has been performed to distinguish the traditional building's resilient and vulnerable features. The qualitative analysis involves detailed inspection of the traditional buildings, interaction with locals to gather further information on construction procedures, comparison of the analyzed traditional buildings with respective codes and guidelines (if available) and literature to assess all the feature's limitations, and recognition of resilient and vulnerable features to earthquakes. Furthermore, based on the survey details, traditional buildings are categorized into earthquake-resilient and earthquake-vulnerable structural systems. A guidance document has been prepared to showcase the earthquake-resilient and vulnerable features of the identified traditional buildings and the measures are suggested to strengthen the vulnerable features in traditional buildings. The primary objectives/outcomes of this project are: (i) identification of traditional buildings, (ii) classification of structural systems of traditional buildings, (iii) identification of earthquake-resilient and vulnerable features (seismic vulnerability) of traditional buildings, (iv) seismic safety measures for vulnerable features seen in traditional buildings, and (v) guidelines/ sketches to construct new traditional buildings.

ACKNOWLEDGEMENTS

The project investigators are grateful to National Disaster Management Authority (NDMA), New Delhi, for readily agreeing to support the preparation of this technical report and companion document on improving the seismic safety of traditional buildings in the Indian Himalayan region. We would like to acknowledge the support provided by Shri Kamal Kishore, Member, NDMA, Shri Krishna Swaroop Vatsa, Member, NDMA, Shri Safi Ahsan Rizvi, Advisor (Mitigation), NDMA, Col. Kirti Pratap Singh, Advisor (Ops & Communication), NDMA, Ms. Sreyasi Chaudhury, Joint Secretary (Mitigation), NDMA, Shri Biswarup Das, Joint Advisor (Mitigation), NDMA, Shri Chandan Singh, Under Secretary (Mitigation), NDMA and Ms. Ranu Chauhan, Consultant (Earthquake & Tsunami), NDMA, New Delhi. We sincerely appreciate all the help we received from them; they provided valuable inputs, generous financial grant towards this project. The investigators also acknowledge the administrative support by NDMA to conduct field surveys during the COVID-19 pandemic.

The credit is also due to the individuals who participated in the field surveys to collect information on the traditional buildings. The project investigators also acknowledge the team of experts, members of Project Monitoring Committee who participated in the project review meetings held to give critical inputs in developing this project report.

HOW TO USE THIS DOCUMENT

This document presents information on the prevalent traditional building practices in the states of Himachal Pradesh, Uttarakhand, Meghalaya, Sikkim, and Assam, and also in the union territory of Jammu and Kashmir, and Ladakh. The detailed information on Kath-Kunni (Koti-banal) buildings in Himachal Pradesh and Uttarakhand, Thathara buildings in Himachal Pradesh, Rammed earth buildings in Himachal Pradesh and Ladakh, Dhajji-Dewari and Taq buildings in Jammu and Kashmir, and Assam-type buildings in the states of Assam, Meghalaya, and Sikkim is presented in this document. The document highlights earthquake-resilient and vulnerable features of the aforementioned traditional buildings and corresponding seismic safety measures. The safety measures recommended in this document are intended to further improve the earthquake resilience of traditional buildings. The safety measures recommended in this document apply to both the existing as well as new traditional buildings. This document can be used to enhance the seismic resilience of Indian housing stock in two ways: (i) the earthquake-resilient traditional building typologies and their earthquake-resilient features can be incorporated in the new constructions to make them earthquake resilient; (ii) the safety measures proposed in this document can be adopted in the traditional building construction to enhance its earthquake resilience. It is hoped that the content presented in this technical report and companion document will prove to be helpful to the academia and government organizations for the dissemination of traditional knowledge of earthquake-resilient building constructions and also to the concerned house owners to construct traditional buildings that are detailed to offer earthquake-resilience and subsequently reduce earthquake risk in the study region.

The study shows that some of the traditional building typologies prevalent in the seismic areas have proven seismic resilient features and need to be promoted in the common house builders. Timber is an excellent building material having inherent seismic resilient properties, and its use in building construction needs to be encouraged. Forest cover depletion and environmental issues are the challenges in this direction, which need to be tackled with long-term policies. The promotion of timber cultivation and high-yield varieties such as bamboo are some of the solutions to meet the timber requirement for the building industry, especially in rural areas. To promote traditional building construction, training skilled manpower is another challenge. It is recommended that the NDMA and SDMAs organize training programs for local artisans, NGOs, and Civil societies to adopt seismic resilient practices in local construction using locally available materials. State/region-specific building typologies, as identified in this report, can be chosen for promotion in different states. The policy of using local materials by local artisans will also lead to livelihood support and a positive environmental impact.

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CHAPTER 1

INTRODUCTION AND SCOPE OF THE WORK

1.1 General Description

The Himalayas are the mountain ranges in Asia that separate the plains of the Indian subcontinent from the Tibetan plateau. The mountain ranges of the Himalayas run for approximately 2400km forming a long arc that stretches from west-northwest to east-southeast, lifted by the subduction of the Indian plate into the Eurasian plate (Fig. 1.1). The Himalayan Mountain ranges spread over five countries: China, Bhutan, Nepal, India, and Pakistan. The Himalayan region is highly vulnerable to earthquakes and has been devastated by multiple strong earthquakes in the past centuries. Many of these strong earthquakes (e.g., 1897 Assam earthquake, 1905 Kangra earthquake, 1950 Assam earthquake, 1975 Kinnaur earthquake, 1991 Uttarkashi earthquake, 1999 Chamoli earthquake, 2005 Kashmir earthquake, 2011 Sikkim earthquake, and 2016 Manipur earthquake) have occurred in the states of India within the Northern and Northeastern region of India (shown by the firm black lines, Fig. 1.1) that had caused significant loss of property and life. Each of the states/union territories in the study region falls under either of the two most severe seismic zones described in India’s latest seismic zonation map (BIS 2016). The discontinuous rupture zones of the past earthquakes have created seismic gaps in the Himalayan region. The measured slip rate, the magnitude of historical earthquakes, and accumulated elastic strain suggest that probability exists for a great mega-thrust type earthquake in the Himalayan region (Thakur 2006). Therefore, assessing the impacts of earthquakes on rural and urban habitats and planning and mitigating earthquake effects are necessary to achieve sustainable development and earthquake risk reduction goals.

Many past earthquakes resulted in significant property loss and human lives in the study region. As a result, communities residing in the study region (shown by the shaded area, Fig. 1.1) swiftly grasped the fundamental premise of earthquake safety, which states that structural safety is the key to avoiding loss of property and human lives in a seismogenic event. This basic understanding by communities of the study region led to the evolution of many innovative traditional building construction practices to minimize human losses from structural collapse during earthquakes (Rautela and Joshi 2009). In addition to the proneness of natural disasters, the study region is also characterized by challenging topographic and climatic conditions. The topographic challenges associated with the study region include the presence of moderate-to-steep and sometimes unstable slopes. Similarly, significant variations in climatic conditions exist, ranging from very hot and humid conditions in some parts to very cold conditions in other areas and significant precipitation in some regions to almost no precipitation in others. As a result, even in the 21st century, many parts of the study region remain inaccessible for quite a significant period over a year. Therefore, many traditional housing typologies have evolved to cater to housing needs. These traditional housing typologies make very judicious use of locally available (natural) construction materials, including timber, stone, rammed earth, mud, etc., for the building construction to achieve dual objectives of climate and disaster resilience.

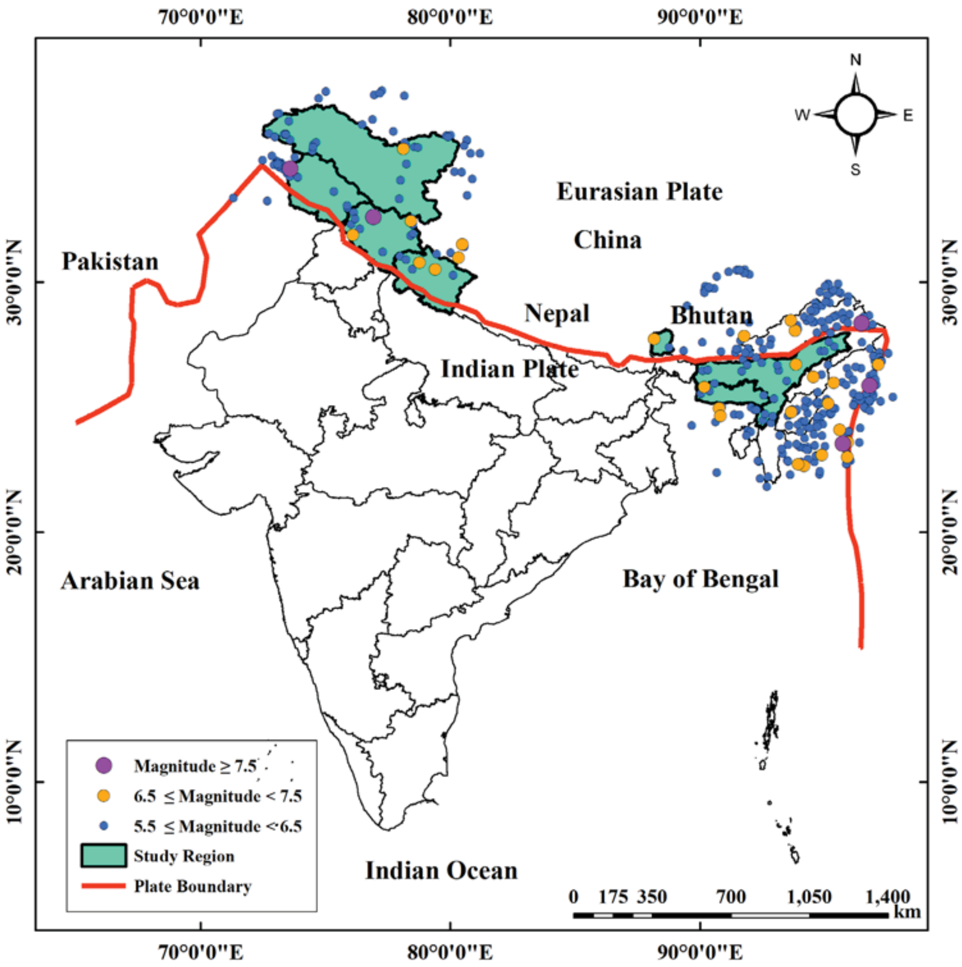


Figure 1.1: Strong earthquakes (magnitude ≥ 5.5) that have occurred in a radius of 500km from the center of northern and northeastern parts of the study region in the past 12 decades are shown on the map of India. The plate boundary shown in red color is adapted from Bird (2003). The earthquake magnitudes and epicenters are adapted from the USGS

Due to frequently occurring earthquakes in the study region (Fig. 1.1), many of the evolved traditional building construction practices in the study region possess several fundamental earthquake-resilient characteristics, including regularity and symmetry in the structure, adequate strength and stiffness, flexibility and deformability, good interconnections between structural elements/components, and reduced seismic mass as their intrinsic features. These traditional buildings have been timely tested under many past earthquakes. Thus, many of them have well-proven records for their earthquake resistance (Sinha et al. 2004). For example, past investigations (Ali et al. 2013) and earthquake damage reports (Rai and Murty 2006; Bothara and Hicyilmaz 2008; Bothara et al. 2022) suggest that 'Dhajji-dewari' and 'Koti-banal' traditional buildings survived strong earthquake shaking without any significant damage. Conversely, the other common building practices (e.g., stone masonry in mud mortar) showed inferior seismic performance, resulting in property and life loss (Arya 1994). Later, the seismic resilience of the traditional 'Dhajji-dewari' and 'Koti-banal' buildings was attributed to centuries of experience gathered and incorporated into their architectural and structural features (Bothara et al. 2022).

To date, limited information is available on the traditional building typologies which are in existence in the study region. For example, the World Housing Encyclopedia (WHE, a joint initiative by the Earthquake Engineering Research Institute, EERI, and the International Association of Earthquake Engineering, IAEE), provides information on the existence of traditional buildings in Himachal Pradesh (Sood et al. 2013a, b; Rahul et al. 2013), Uttarakhand (Rautela et al. 2009), Jammu and Kashmir (Hickyilmaz et al. 2011), Assam (Kaushik and Babu 2009), and Nagaland (Khan 2008). Nowadays, due to the combined effects of (i) ease in transportation and availability of the modern construction materials (e.g., bricks, cement, reinforcing bars, etc.) used for contemporary buildings at a comparative cost, (ii) scarcity of the materials used for traditional constructions, especially 'timber' (since the tree falling is banned by the government(s) for newer constructions and 'The Indian Forest Act' (1927) does not permit the use of forest timber for building construction), and (iii) lack of availability of skilled artisans knowing traditional building construction, many occupants of the traditional buildings are moving towards the construction of contemporary buildings. As a result, the original forms of these traditional construction practices of the study region are becoming less feasible (Zanden 2018), and the traditional knowledge of earthquake-resilient building construction in the study region is slowly vanishing.

The presented facts highlight a need to collect detailed information on the traditional (indigenous) knowledge for building construction, track their variations over time, document them for knowledge sharing, highlight their good/seismically-resilient features for promotion, and subsequently reduce earthquake risk in the study region. In addition, a few of these traditional construction practices also have seismically-vulnerable elements. Thus, it also becomes necessary to identify those earthquake-vulnerable elements and suggest essential safety measures to enhance their earthquake resistance. Accordingly, to address the aforementioned aims, the project objectives have been formulated and described in the subsequent sections of this report.

1.2 Project Objectives

The work conducted within the scope of the project has the following objectives:

1. To identify and document the traditional building typologies in the study region;
2. To classify structural systems of traditional buildings in the study region;
3. To assess the seismic vulnerability of traditional buildings in the study region; and
4. To suggest seismic safety measures for the identified traditional building types.

1.3 Scope of the Work and Methodology

The scope of the current project is to identify and document the traditional building types in the study region and develop their structural system classification scheme. Accordingly, in the present study, extensive field surveys have been conducted primarily in the states of Himachal Pradesh, Uttarakhand, Meghalaya, Sikkim, Assam, the union territory of Jammu and Kashmir, and Ladakh. Several teams from the participating institutes have conducted the field surveys, each comprising at least two structural engineers. Detailed information has been collected on the existing traditional building typologies of the study region. These details include the siting aspects, architectural features, structural features, soil conditions and foundations, and the buildings' visual condition (current health) and maintenance. The collected information from the field surveys is presented in photographs and sketches, and a structural classification for traditional buildings is developed.

Seismic vulnerability assessment is an integral step in planning and identifying the strengthening needs for the existing buildings and upgrading them to achieve the acceptable performance of structures under earthquakes. Various methods are available in the literature for seismic vulnerability assessments, and those can be broadly categorized into quantitative and qualitative methods. The quantitative methods are differentiated regarding the approaches and assumptions used to correlate physical damage with a ground-motion intensity measure. They can generally be categorized into three groups: (i) empirical methods (Rossetto and Elnashai 2003), (ii) analytical methods (Singhal and Kiremidjian 1996), and (iii) expert judgment-based methods. In practice, many efforts combine two or more of these approaches, leading to some hybrid methods (Kappos et al. 1998). Empirical methods of seismic vulnerability assessment rely on post-earthquake damage observations and are therefore considered the most promising approach to seismic vulnerability assessment for any particular region. These methods are often based on macroseismic intensity scales (e.g., Modified Mercalli Intensity (MMI), MSK Intensity) or PGA to represent the ground-motion intensity. In the context of the study region considered in the present study, although the region has suffered several devastating earthquakes, only very few systematic post-earthquake damage surveys have been conducted so far (Sharma et al. 2011; EERI 2012). The quantity and quality of available data do not ensure a proper in-depth vulnerability analysis of traditional buildings using the empirical approach. In contrast, the analytical seismic vulnerability assessment requires material characterization and structural behavior simulation to develop the relationship between physical damage and ground motion intensity. To date, minimal information is available on the mechanical properties of materials used in traditional buildings. Because of the inherent variability and complexity of the individual materials, component interactions, and forms of traditional construction, it is not possible to accurately model the structural behavior of traditional buildings. Thus, the standard analysis techniques appropriate for the dynamic analysis of engineered structures have limited validity when applied to traditional buildings. Therefore, the application of the analytical approach of seismic vulnerability assessment is challenging in the context of traditional buildings.

The present study aims to identify the earthquake-resilient and vulnerable features in the traditional buildings existing in the study region and suggest the appropriate safety measures to reduce their seismic vulnerability. Accordingly, the qualitative seismic vulnerability assessment method has been employed in the present study. The past studies (Murthy et al. 2012) and the provisions/recommendations of Indian standards (BIS 1986, BIS 1993a, BIS 1993b, BIS 1993c, BIS 2016) are used to investigate the seismic vulnerability of traditional buildings considering the building's (i) siting (i.e., location of a building site), (ii) architectural features (e.g., openings in walls, location of openings in walls, number of stories, story heights, projections, the gap between two adjacent buildings, etc.), (iii) structural features (e.g., wall thickness, wall-to-wall connection, wall-to-floor/roof connections, structural wall density, etc.), (iv) soil conditions and foundation (e.g., type of ground strata, and foundation sizes), and (v) and visual condition and maintenance aspects of the buildings. Based on the details collected from the field surveys, all the identified traditional building typologies are analyzed qualitatively for their seismic vulnerability, using the fundamental principles of earthquake safety. Moreover, various earthquake-resilient features and seismic deficiencies of the prevalent traditional building types in the study region have been identified and highlighted. The seismic safety measures (in the form of sketches) from the existing literature are suggested for the commonly observed deficiencies in the traditional building practices of the study region, which will be helpful in further reducing the seismic vulnerability of traditional buildings.

1.4 Organization of the Project Report

The project report has been organized into eight Chapters:

Chapter 1 presents an introduction to the project, the project objectives, the scope of the work, the methodology, and the organization of the report.

Chapter 2 presents the details of earthquake-resilient traditional building types observed during the field surveys in the study region. These details include the region of existence of a traditional building typology at the district level, their siting aspects, architectural features, structural features, soil conditions and foundations, visual condition and maintenance, and contemporary modifications (if any). The chapter also discusses the effects of all these features on the seismic vulnerability of traditional buildings, and the seismic performance of these buildings under past earthquakes and highlights the seismically-resilient/vulnerable features of each traditional building typology. Seismic safety measures are suggested to improve traditional buildings' earthquake resilience further.

Chapter 3 presents the details of earthquake-vulnerable traditional building types observed during the field surveys in the study region. These details include the region of existence of a traditional building typology at the district level, their siting aspects, architectural features, structural features, soil conditions and foundations, visual condition and maintenance, and contemporary modifications (if any). The chapter also discusses the effects of these features on the seismic vulnerability of traditional buildings and the seismic performance of these buildings under past earthquakes and highlights the seismically-resilient/vulnerable features of each traditional building typology. Seismic safety measures are suggested for further improving the earthquake resilience of existing and new traditional buildings.

Chapter 4 presents the structural system classification of traditional buildings considering the various essential attributes of the traditional buildings including siting (structural configuration), height, load-bearing system, floor and roof systems, and foundations observed during field surveys in the study region.

Chapter 5 presents the typical sketches of the recommended seismic safety measures that can be used in the construction of new traditional buildings and also to improve the seismic performance of the existing traditional buildings in the study region.

Chapter 6 summarizes the key findings of the project work, highlighting the earthquake-resilient and vulnerable features of traditional buildings, and safety measures.

Chapter 7 presents the recommendations of the study.

Chapter 8 presents the way forward.

CHAPTER 2

EARTHQUAKE-RESILIENT TRADITIONAL BUILDINGS

2.1 General Description

The Himalayan arc has a rich heritage in earthquake-resilient traditional construction practices. Depending on the local availability of the materials, the socioeconomic status of the communities, and climatic conditions, several traditional building typologies have evolved in the Himalayan region. One of the interesting facts about these traditional buildings is that the commoners have incorporated centuries of experience in the architectural and structural features using the trial-and-error method. The existing literature suggests the existence of multiple traditional earthquake-resilient building practices in the northwestern Himalayas within India. These traditional building practices mainly include the timber-laced stone masonry without mortar, indigenously known as ‘Koti-banal’ or ‘Kath-kunni’ (Rautela et al. 2009a, Rautela et al. 2009b), the timber frame with dry stone walls indigenously known as ‘Thathara’ (Rahul et al. 2013), the timber-braced frame infilled with brick/stone masonry laid in mud mortar indigenously known as ‘Dhajji-dewari’ (Hicyilmaz et al. 2011), and the timber-laced brick/stone masonry laid in mud mortar indigenously known as ‘Taq’ (Dhandhapany et al. 2019). Similarly, northeast India’s traditional seismically-resilient building practice mainly includes the timber frame infilled with ‘Ekra’ reeds, indigenously known as ‘Assam-type’ or ‘Ekra’ (Kaushik and Babu 2009) housing.

In this Chapter, the earthquake-resilient traditional building types in the study region are identified and discussed in detail. A random sample-based field survey approach has been used to identify the earthquake-resilient traditional building types prevalent in the study region. The project team conducted extensive field surveys in the study region, and more than 200 traditional buildings were surveyed within the study region in the Northern and Northeastern parts of India. The details of all the prevalent (existing) traditional earthquake-resilient building practices in terms of their siting, architectural features, structural features, soil conditions, foundations, visual conditions, and maintenance were collected from the field surveys. Detailed sketches describing the important architectural features, structural features, and foundations of these traditional building typologies are developed from the collected details. As a part of the field surveys, detailed discussions regarding the seismic performance of these buildings during past earthquakes and the general maintenance of these buildings were also carried out with the locals in the study region. The necessary photographs captured during the field surveys and relevant details and discussions are also presented in this Chapter.

2.2 Kath-kunni Buildings

2.2.1 Introduction

Kath-kunni construction is one of the oldest forms of traditional construction widely seen in Shimla, Kullu, Kinnaur, and Mandi districts in Himachal Pradesh (Fig. 2.1) and Uttarkashi in the state of Uttarakhand. This traditional building type is known as Koti-Banal architecture in and around the Rajgarhi area of Uttarkashi, Uttarakhand. Kath-kunni originated from the parent construction material used in this traditional building typology, where 'Kath' means 'timber' and 'Kunni' means 'corner'. Hence, traditionally the buildings with timber corners are called 'Kath-kunni.' This form of traditional building construction practice is prevalent and widely used by people of poor-to-high socioeconomic levels. It is predominantly found in high-altitude regions, where timber was abundant at the time of its construction.

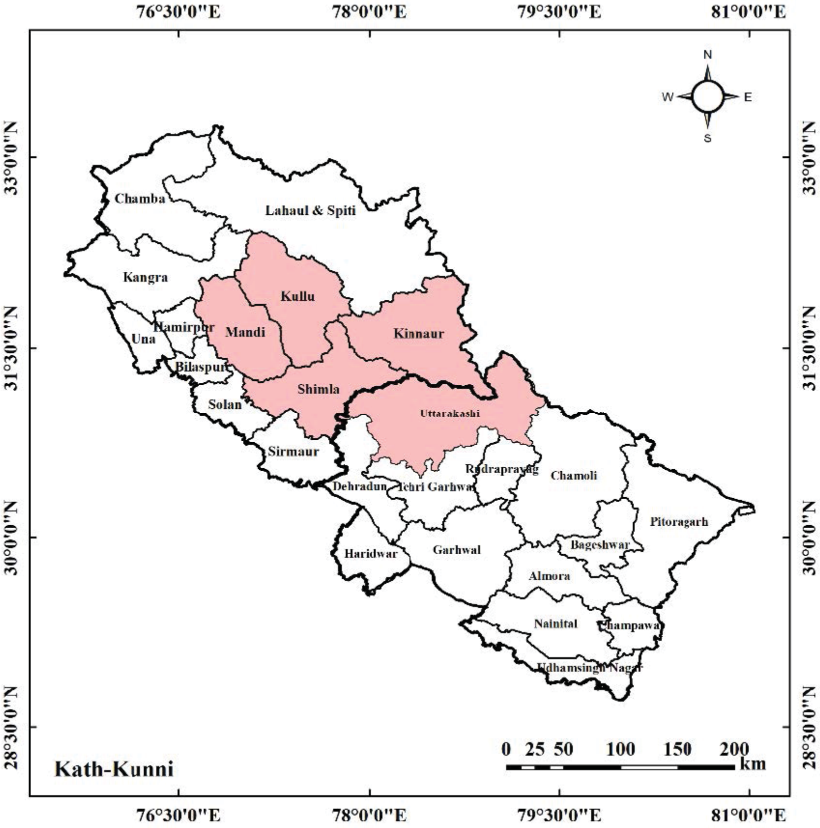


Figure 2.1: Map showing the regions of the prevalence of the Kath-kunni buildings

The traditional Kath-kunni style of building construction makes very judicious use of locally available stones (usually obtained from surrounding hills/stone quarries by breaking large rocks into smaller pieces giving them the shape of semi-dressed/dressed stones of uniform thickness roughly) for the construction of walls, Deodar/Kail timber elements in the construction of walls, floors, and roofs, stone slates, wooden planks, and corrugated galvanized iron (CGI) sheets to cover roofs (though this is a new addition), and mud which is a good insulator of heat for plastering on the internal and sometimes also on the external faces of the walls. The timber, primarily used in walls, floors, and roofs, is no longer available, mainly due to the ban on trees falling. Therefore, new buildings of the traditional Kath-kunni style in the region are no longer being constructed. However, up-gradation/repair of Kath-kunni buildings can be seen around Naggar in Kullu. Kath-kunni buildings have higher service life when compared to other building practices, mainly due to the use of highly durable materials (i.e., dressed/semi-dressed stones and Deodar wood) that have excellent waterproofing properties. During field surveys, the occupants recollected that many of these Kath-kunni style buildings in Himachal Pradesh have been in existence for the past 4-5 generations or even longer. The villages where the Kath-kunni buildings are still in existence include Sainj, Rohru, Blog, Kath, and Chopal in the district of Shimla, Himachal Pradesh; Kaees, Archandi, Hirni, New Manali, Mansari, Sarsail, Naggar, Rumsu, Sharan in the district of Kullu, Himachal Pradesh; Ribba, Moorang, Sangla, Rakcham, Karcham, Batseri, Chitkul in the district of Kinnaur, and Kangu, Bayla, Panjain, Banjar and Ropa in the district of Mandi, and in and around Rajgarhi areas of Uttarakhand. These villages fall in the Indian Seismic Zones IV or V as per India's current seismic zonation map (BIS 2016).

2.2.2 Siting

The siting of a building plays a crucial role in achieving adequate seismic performance. Generally, sites with flat terrain for building construction are usually preferred due to frequent unstable slope failure in the study region. However, selecting sites with flat terrain is not always possible due to the region's topography. As a result, three different siting possibilities have been observed in the construction of Kath-kunni buildings: (i) the building is located on flat ground (Fig. 2.2(a)), (ii) the building is located on sloped ground, with a raised dry-stone platform (Fig. 2.2(b)-(c)), and (iii) the building is located on the sloped ground with a raised wooden platform (Fig. 2.2(d)). The height of the dry stone/wooden raised platform can be up to 2.0 m. In the case of Kath-kunni buildings constructed on slopes, the observed slope gradient does not exceed 2:1 (H: V). Photographs showing siting features of the Kath-kunni buildings collected during field surveys are presented in Fig. 2.2.

(a) On flat ground (b) On a raised dry-stone platform

(c) On a raised dry-stone platform (d) On a raised wooden platform

Figure 2.2: Different siting observed in Kath-kunni buildings

2.2.3 Architectural Features

The primary purpose of the Kath-kunni style of traditional building construction practice is to provide shelter to human beings. Thus, it is mainly used for residential occupancy (Fig. 2.3). However, this traditional construction style can also be seen in many of the old and newly built temples (Fig. 2.3) in the state of Himachal Pradesh. During field surveys, two variants of these traditional buildings were observed (Fig. 2.4). The first variant is seen in the districts of Kullu, Mandi, and Shimla (here onwards referred to as 'KK1', Fig. 2.4(a)), and (ii) the second variant is seen in the district of Kinnaur (here onwards referred to as 'KK2' Fig. 2.4(b)). The former variant (i.e., 'KK1') was observed to have three-to-five stories (Fig. 2.4). In contrast, the latter (i.e., 'KK2') variant was observed to have only two stories (Fig. 2.4). The Kath-kunni buildings of Shimla, Kullu, and Mandi have unique characteristics of lesser built-up areas and more stories to fulfill the space requirements for single-family housing. The lower two floors in this style of construction are utilized for the cattle and for the storage of food grains (generally, the lowermost floor is used for cattle and the floor above it for the storage of food grains), and these stories have significantly smaller story heights, usually lower stories height vary between 1.2-1.5 m, whereas the upper stories are used for living spaces, and the story heights in the upper stories vary between 2.0-2.2 m. The other variant of the Kath-kunni style of construction prevalent in Kinnaur has 2-stories with a story height of 1.75-2.0 m (Fig. 2.5) in which the ground story is used for the cattle, and the upper story is used as living space. A separate construction unit for storing food grains was constructed in the variant mentioned above, locally known as Urch/Kothar (Fig. 2.6).

(a) Temple building (b) Temple building

(c) Temple building (d) Residential building

Figure 2.3: Different occupancies observed in Kath-kunni buildings

The field investigations conducted in the states of Himachal Pradesh and Uttarakhand revealed that both the variants of the Kath-kunni style of traditional building construction consider the fundamental premise of earthquake safety of the building in their architecture by selecting a robust structural configuration, maintaining the symmetry in their plan and regularity in their elevations. It has been observed that most of the Kath-kunni buildings are rectangular plan shaped with their plan aspect ratios in the range of 1.1-1.4 (Fig. 2.7). The typical lengths and widths of Kath-kunni buildings are in the range of 3.5-8 m. The Kath-kunni buildings have small entrances in the ground story without any windows. Staircases are provided internally to access the upper floors. The Kath-kunni style of traditional construction includes doors and windows of minimal sizing (typically, total openings do not exceed 15% of the length of the wall) (Fig. 2.8), which are mostly placed centrally.

(a) Residential building (KK1) (b) Residential building (KK2)

Figure 2.4: Variants of the Kath-kunni buildings observed in the study region

(a) Small story height @ 1.8 m (b) Small story height @ 1.9 m

Figure 2.5: Small story heights in Kath-kunni buildings

(a) Urch with timber planks (b) Urch with CGI sheets

Figure 2.6: Urch construction practice along with KK2 buildings

(a) Rectangular plan shape (b) Rectangular plan shape

(c) Rectangular plan (d) Rectangular plan

Figure 2.7: Plan shapes observed in Kath-kunni buildings

(a) Small openings (b) Small openings

(c) Small openings (d) Small openings

Figure 2.8: Openings in Kath-kunni buildings

In Kath-kunni buildings, no vertical projections were observed. On the other hand, horizontal projections exist almost in all Kath-kunni buildings. Usually, on the uppermost floor, a balcony is provided to take sunbaths and to protect the building occupants from rain and snow in both variants of the Kath-kunni construction. The length of horizontal projections is usually between 1.2-1.5 m (Fig. 2.9). Mostly, the Kath-kunni buildings are constructed in isolation. Therefore, a sufficient gap exists between the two buildings. However, in a few cases, closely spaced Kath-kunni buildings were also seen (Fig. 2.10), with the distance between them varying from 0.3-1.2 m.

(a) Small projections (b) Small projections

(c) Small projections (d) Small projections

Figure 2.9: Horizontal projections in Kath-kunni buildings

(a) The gap between adjacent buildings (b) The gap between adjacent buildings

Figure 2.10: Distance between adjacent Kath-kunni buildings

2.2.4 Structural Features

2.2.4.1 Load-bearing Wall Systems

The load-bearing system of Kath-kunni buildings can be categorized as timber-laced stone masonry construction without any mortar. Kath-kunni buildings have been observed in various wall thicknesses ranging from 0.30-0.90 m, with 0.45 m thick walls being the most common. Small story height, along with the reported high wall thickness, ensures that the height-to-thickness ratios in walls of Kath-kunni buildings are not exceeding 6 (Fig. 2.11). An equal distribution of walls exists in two horizontal directions, with wall lengths usually not exceeding 5 m (Fig. 2.11). The structural wall plan density for Kath-kunni buildings can range from 25-35%. The higher wall plan density in Kath-kunni construction is associated with a greater number of stories. The load-bearing walls in Kath-kunni buildings are laid in courses of semi-dressed/dressed stones (without any mortar) and closely spaced timber bands, oriented in two horizontal building directions at multiple levels along the height of the wall (Figs. 2.11-2.13). The horizontal timber members (runners) in the walls are placed on all four sides at the inner and outer edges of the walls. These horizontal runners are further interconnected through timber links (locally called 'Maanvi' or 'Makdi' Fig. 2.14) using double dovetail connections (Fig. 2.14), at an approximate spacing of 0.50 m. The vertical spacing (internal-to-internal) between timber bands is almost equal to 0.15 m in the old temple/residential buildings (Figs. 2.11 and 2.12). On the other hand, in the relatively newer Kath-kunni buildings, the vertical spacing between timber bands seems to have increased up to 0.45 m, and sometimes bands are seen at the plinth and roof levels. These horizontal timber bands are arranged one above another in two perpendicular walls and inter-connected through timbers nails (locally called 'Kadil,' Fig. 2.14) of size 0.04 m × 0.04 m at all four corners of the walls. Sometimes, mud/cow dung is used as the plastering material on both the internal and external faces of the walls (Fig. 2.13). Intermediate lap-jointed connections are used in longer walls when wooden elements are less than the wall lengths. The wooden logs at the bottom of the walls are embedded into the base platform.

(a) Wall thickness @ 0.30 m

(b) Wall thickness @ 0.90 m

(a) Small wall length

(b) Small wall length

Figure 2.11: Wall thickness and wall lengths in Kath-kunni buildings

(a) Wall-to-wall connections

(b) Wall-to-wall connections

(c) Depth of the band

(d) Spacing between bands

Figure 2.12: Timber bands in Kath-kunni buildings

(a) No plaster

(b) Mud plaster

(c) Mud plaster

(d) Mud plaster

Figure 2.13: Plasters on the external faces of walls in Kath-kunni buildings

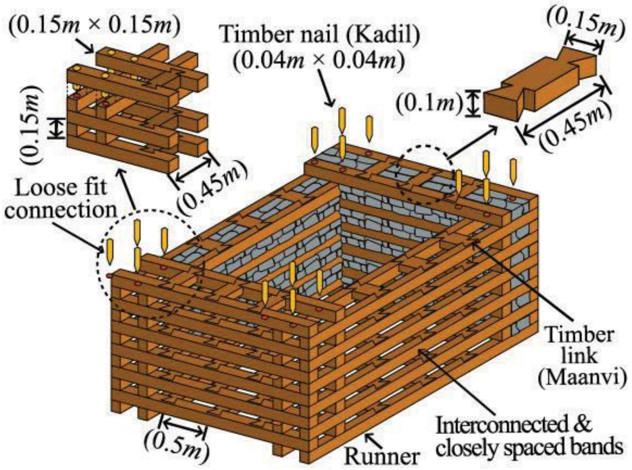


Figure 2.14: Typical sketch of the load-bearing system of Kath-kunni buildings

2.2.4.2 Floor Systems

Different floor systems are employed in Kath-kunni buildings on the ground floor and upper floors. The ground floor in the Kath-kunni building usually consists of stone filling overlaid by mud flooring in residential buildings. In the case of temples, stone flooring is adapted on the ground floor (Fig. 2.15(a)). Timber planks supported on timber floor joists are used as the floor system on the upper floors (Figs. 2.15 and 2.16). The thickness of timber planks used in the floor system varies between 0.02-0.025 m. The floor joists (0.10 m × 0.15 m) usually span in a shorter direction, with a single member covering the entire building width. These floor joists are nailed to the timber band below them to provide floor-to-wall connections. The Kath-kunni buildings have cantilever projections of timber elements (0.10 m × 0.15 m) on all four sides inserted into the walls nailed to the timber band just below them. They are tied together at the opposite end using the supporting beam on all four sides of the building. The timber planks are further nailed to the floor joists (Figs. 2.11 and 2.15-2.16). Cross-planks or any other arrangements are not seen in the floor system of Kath-kunni buildings, and thus, the floor system in Kath-kunni buildings is expected to behave as a flexible diaphragm.

2.2.4.3 Roof Geometry and Systems

Roof systems in the traditional Kath-kunni style of construction in Shimla, Mandi, and Kullu have Dutch-gable roofs (Fig. 2.17) with stone slate (Fig. 2.17 (a)) to cover the roofs that are supported on timber elements. Contrary to this, timber planks are used to cover roofs in the traditional Kath-kunni style of construction, primarily found in Kinnaur (Fig. 2.17(b)), with few exceptions, where timber planks are replaced by CGI sheets or stone slates due to significant degradations in the timber over time. The stone slates in the roof cover are nailed to the roof system. The primary reason for using a Dutch-gable roof in the traditional Kath-kunni buildings is to allow the snow to slide over the roof surface in the winter season, as the area suffers snow cover for at least two to three months a year. In Kath-kunni buildings, walls on the uppermost floor are extended to create a triangular (gable) shape of the roof system (Figs. 2.17 and 2.18). The timber elements of cross-sections 0.10 m × 0.15 m are cantilevered from the walls, and inclined members are connected at one end using nails (Fig. 2.18). The cantilevered roof elements are connected and tied to timber supports on all four sides (Figs. 2.18). In the roof support system, timber members are oriented in two orthogonal directions connected at ends through grooves and also in the diagonal direction (Fig. 2.18), which are further inserted into the walls. These wooden members are usually kept at a spacing of 1.0-1.5 m. The cross-section size of the timber elements is typically 0.15 m × 0.10 m. The vertical rise of the roof can vary between 1.0-1.5 m. The typical sketch of the roof system is shown in Fig. 2.18.


(a) Stone flooring (b) Mud flooring over timber planks


(c) Timber planks on timber floor joists (d) Timber planks on timber floor joists


(e) Timber planks on timber floor joists (f) Timber planks on the floor

Figure 2.15: Floor system in Kath-kunni buildings

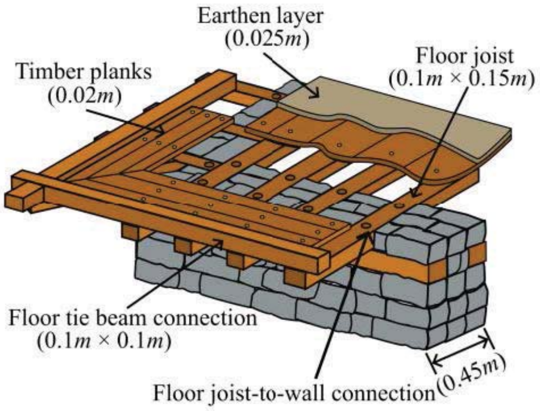


Figure 2.16: Typical sketch of the floor system in Kath-kunni buildings

(a) Dutch-gable roof with stone slates

(b) Gable roof with timber planks

(c) Roof system

(d) Roof system

(e) Roof system in the balcony

(f) Vertical posts in the roof system supporting rafters

Figure 2.17: Roofing material and systems in Kath-kunni buildings

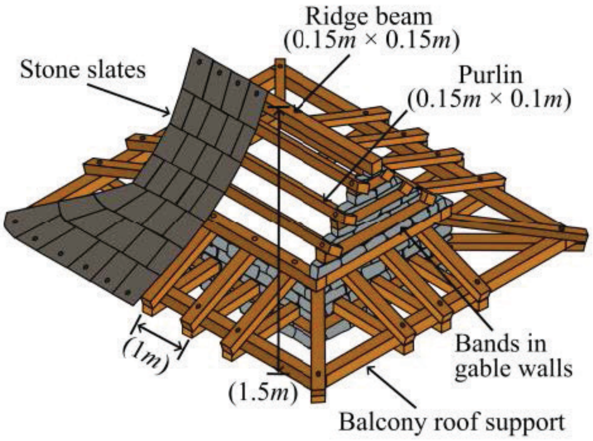


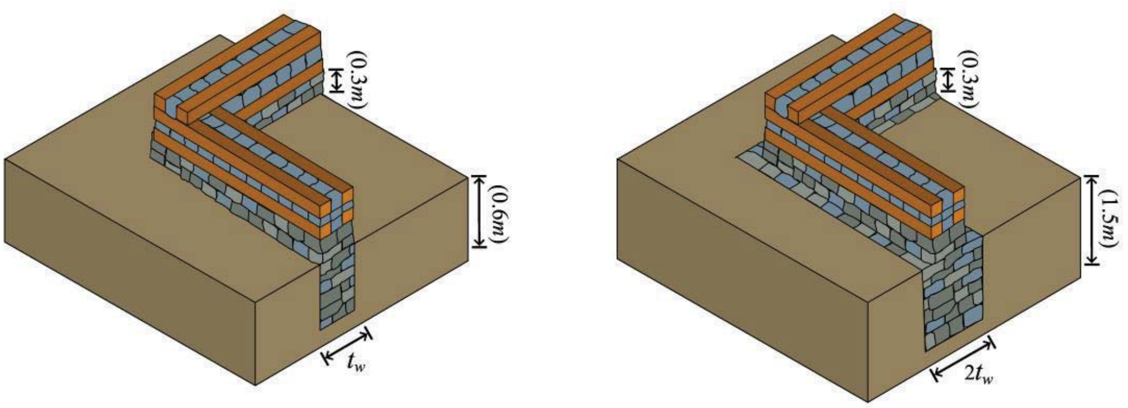
Figure 2.18: Typical sketch of the roof system in Kath-kunni buildings

2.2.4.4 Soil Conditions and Foundations

Strip foundations of river/field stones are used in Kath-kunni buildings (Figs. 2.19 and 2.20). The foundations' sizes (i.e., width and depth) in traditional buildings are chosen depending on the type of ground strata available at a particular site. The width of the foundation is kept identical to the thickness of the wall when a building is constructed on bedrock. It is increased to 1.5-2.0 times the thickness of walls when the building is built on medium to weak soils. Similarly, the depth of the foundation varies between 0.6-1.0 m when the building is constructed on bedrock, and it is increased up to 1.5 m when medium to weak soils are encountered. Sometimes, in the Kath-kunni buildings, the foundation depth is increased up to 2.0 m due to thicker walls and a greater number of stories. The typical sketches of the foundations are shown in Fig. 2.20. The discussions with locals further revealed a traditional practice used in the foundations of Kath-kunni buildings, in which the foundation is primarily constructed, followed by the construction of the superstructure that begins only after the rainy season ends. This practice ensures the safety of buildings against foundation/ground settlements that are expected to occur in soft soils during and after the rainy season.

(a) Stone foundation (b) Stone foundation

Figure 2.19: Foundations in Kath-kunni buildings



(a) Foundation on hard soil (b) Foundation on soft soil

Figure 2.20: Typical sketches of foundations in Kath-kunni buildings

2.2.5 Visual Conditions and Maintenance

The owners maintain the Kath-kunni buildings. The visual conditions for most of the Kath-kunni buildings have been observed to range from average to good, except for a few buildings, particularly in Chitkul (Kinnaur), which were heavily deteriorated and unoccupied (Fig. 2.21). Non-maintenance of a few Kath-kunni buildings over a longer period resulted in them being too weak to use for residential purposes. The discussions with locals revealed that the scarcity of timber and lack of skilled artisans are other causes for their non-maintenance. The other primary source of deterioration in Kath-kunni buildings is the degradation of wooden planks in the roof systems due to their direct exposure to rain and snow. The heavily deteriorated buildings in Chitkul were unoccupied.

(a) Deteriorated building (b) Deteriorated building

Figure 2.21: Deteriorated Kath-kunni buildings in the study region

2.2.6 Contemporary Modifications

Few buildings are seen that were originally constructed in the Kath-kunni style and later on modified with minor interventions using contemporary construction materials. These modifications include the partitions made using burnt clay bricks, cement plaster, and CGI sheets. The typical photographs depicting the influence of modern materials in Kath-kunni buildings are shown in Fig. 2.22.

(a) Brick walls in Kath-kunni (b) Brick walls in Kath-kunni

(c) Brick walls in Kath-kunni (d) CGI sheets in Kath-kunni

Figure 2.22: Influence of contemporary materials on Kath-kunni buildings

2.2.7 Past Seismic Performance and Vulnerability

The investigations conducted in this study suggest the origin of the Kath-kunni construction at least 8-10 centuries before or even more. There is evidence in the literature (Rautela and Joshi, 2007) wherein through radiocarbon dating, some of the existing buildings of the Kath-kunni (Koti-banal) style are found to be approximately 880 ± 90 years old. The Himalayan region where Kath-kunni buildings are prevalent faced several strong earthquakes in the past few centuries. A few of these earthquakes include the 1720 Kumaun earthquake (M>8), the 1803 Garhwal earthquake (Mw=8.1), the 1897 Assam earthquake (Mw=8.1), the 1905 Kangra earthquake (Mw=7.8), the 1934 Bihar Nepal earthquake (Ms=8.1), the 1950 Assam earthquake (M=8.6), the 1975 Kinnaur earthquake (Ms=6.8), the 1991 Uttarkashi earthquake (Mw=6.8) and the 1999 Chamoli earthquake (Mw=6.6). When asked about the performance of the Kath-kunni buildings, the occupants recollected and replied that no significant damage was observed in the recent earthquakes (those that have occurred in the past 3-4 decades) in Kath-kunni buildings. Many of these Kath-kunni style buildings have stood firm for the past two-three centuries. Further, the post-earthquake damage reports (Gülkan and Langenbach 2021; Langenbach 2003; Langenbach 2015, Rai and Murthy 2006) for the Himalayan region suggest the excellent performance of timber-laced masonry buildings, though these reports specifically talk about ‘Taq’ construction. These facts highlight the superior performance of these buildings under several past earthquakes compared to other regional building practices.

Even though these Kath-kunni buildings survived several past earthquakes, there are a few specific features of these Kath-kunni buildings that could add to their seismic vulnerability. The features that add to their seismic vulnerability are thicker walls made of stones and stone slate roofing which are heavy-weight and attract higher earthquake forces. The floor planks are nailed to the floor joists, thus, offer limited in-plane rigidity unless nailed extensively. Similarly, the absence of bracings in the roof system makes them flexible in their plane. As a result, both the floors and roofs in Kath-kunni buildings do not provide full restraint to walls against out-0f-plane movements. Further, some buildings are heavily deteriorated and hence pose threat to collapse under earthquakes.

2.2.8 Earthquake-Resilient Features

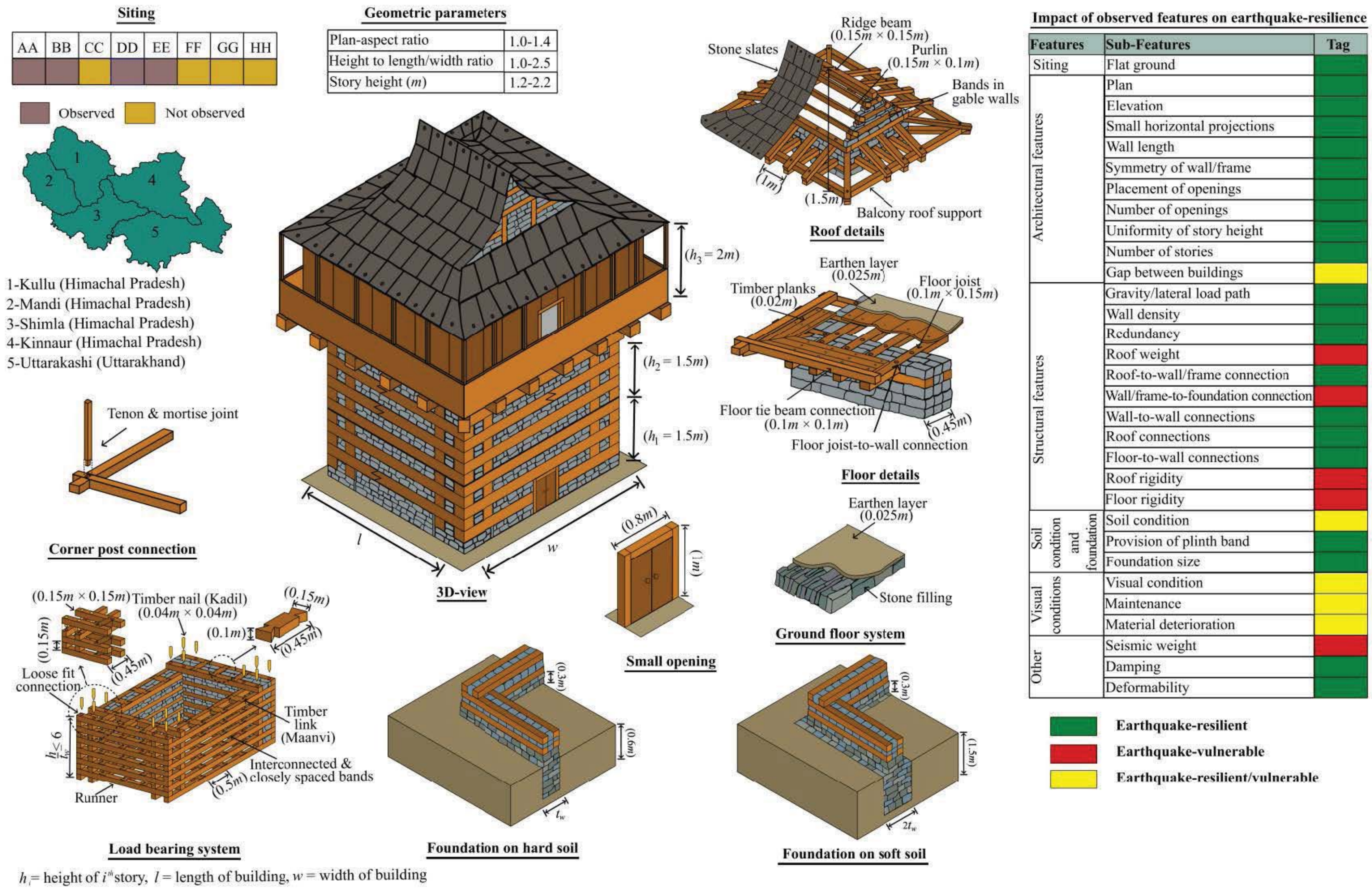
Kath-kunni buildings possess several earthquake-resilient characteristics in their siting, architectural, and structural features, as summarized in Fig. 2.23. Starting from the site selection, it is usual practice to construct these buildings on flat terrain or create flat terrain artificially using raised dry-stone/wooden platforms. As a result, these buildings are regular in shape in both plan and elevation. The plan dimensions of the Kath-kunni buildings are chosen to result in a plan shape closer to the square shape. Hence, these buildings offer approximately comparable strength and stiffness in two horizontal directions. Smaller story heights and total building height ensure a low height-to-width ratio for these buildings. These buildings are further characterized by very small door and window openings, mostly placed centrally, resulting in a larger area of walls available to resist seismic actions. A relatively larger quantity of stones in the lower portion and timber in the upper portion of Kath-kunni buildings minimizes the overturning effects and provides overall stability to these buildings. These buildings in rural areas are constructed mostly in isolation. Thus, pounding is not expected to occur for Kath-kunni buildings.

The unsupported wall lengths in Kath-kunni buildings do not exceed a length of 5 m. The high wall thickness and small story heights ensure the slenderness ratio of walls, typically below 6, and provide resistance to out-of-plane overturning. Using long stones at the junction of walls and interconnected timber bands provides wall-to-wall connections, and tie the walls together thereby transferring the loads from out-of-plane loaded walls to the connected perpendicular walls and helping maintain the integrity of the building. The resistance to shear forces is developed by the friction between the adjoining elements (i.e., between stone and stone and between timber and stone). The presence of closely spaced multiple bands, along with the height of the walls, further prevents vertical cracking at the corners and ensures safety against the out-of-plane collapse of walls. The floor systems in Kath-kunni buildings have suitable loose-fit interconnections with the walls, and floor joists are tied together with the walls. As the floor joists usually span shorter building directions, the lateral loads in Kath-kunni buildings are transferred to the ground primarily through longer walls. The roof system in Kath-kunni buildings has good interconnections with the walls, and roofs are tied together on all four sides with walls. The gable walls are provided with multiple timber bands; thus, failure of the gable end is also prevented in Kath-kunni buildings. The past experimental investigations (Magenes et al. 2014) suggest that full in-plane capacities of stone masonry walls can be exploited even with a flexible diaphragm, provided the walls are restrained against the out-of-plane forces. Therefore, even though, the floor and roof diaphragms are flexible in Kath-kunni buildings, their flexibility is not expected to increase the seismic vulnerability of Kath-kunni buildings. Most Kath-kunni buildings rest on rock/hard soil, which is also a desirable feature for their earthquake resistance.

Apart from these siting, architectural, and structural features, Kath-kunni buildings possess other important engineering characteristics related to their construction materials and structural connections that benefit their enhanced earthquake resistance. The dressed stones filled in between timber bands in Kath-kunni buildings led to the following essential actions: (i) timber bands along with stones provide the deformability to the Kath-kunni buildings, and thus, increased energy dissipation capacity, and (ii) the timber and stones in walls of Kath-kunni buildings develop good frictional resistance and possess high damping ratio (10% of the critical damping in the undamaged state, Bothara et al. 2019; Bothara et al. 2022) as compared to contemporary materials (e.g., reinforced-concrete, where it is 5% of the critical damping in the undamaged state). The high damping ratio reduces the seismic force demands on Kath-kunni buildings. The other important features of Kath-kunni buildings are 'loose-fit' (semi-flexible) connections among structural elements of walls, floors, and roofs, allowing the deformations in the buildings and various components in a controlled manner and leading to good energy dissipation capacity.

2.2.9 Suggested Seismic Safety Measures

As discussed in the previous section, the floors and roofs of the Kath-kunni buildings are expected to behave as flexible diaphragms. Therefore, to improve the in-plane rigidity of the floors and roofs, the necessary measures for the Kath-kunni buildings are suggested and shown in Fig. 2.24. Further, as discussed earlier in this report, new Kath-kunni buildings in the study region are not constructed; hence, the safety measures suggested apply to the existing Kath-kunni buildings. The in-plane rigidity of the floor system of Kath-kunni buildings can be improved either by providing and connecting additional timber planks perpendicular to the existing timber planks using nails, cross-timber planks or by providing carbon fiber reinforced polymer (CFRP) straps using epoxy diagonally (adapted from Gattesco and Macorini 2014) as shown in Fig. 2.24. Further, to improve the rigidity of the roof system in Kath-kunni buildings, timber/metal diagonal bracings can be added and connected to the roof. The seismic weight of roofing can also be reduced using lightweight roofing (e.g., CGI sheets). However, these roof coverings may be less durable and require periodic replacements.



Siting

AA	BB	CC	DD	EE	FF	GG	HH
🟫	🟫	🟨	🟫	🟫	🟨	🟨	🟨

🟫 Observed 🟨 Not observed

Geometric parameters

Plan-aspect ratio	1.0-1.4
Height to length/width ratio	1.0-2.5
Story height (m)	1.2-2.2

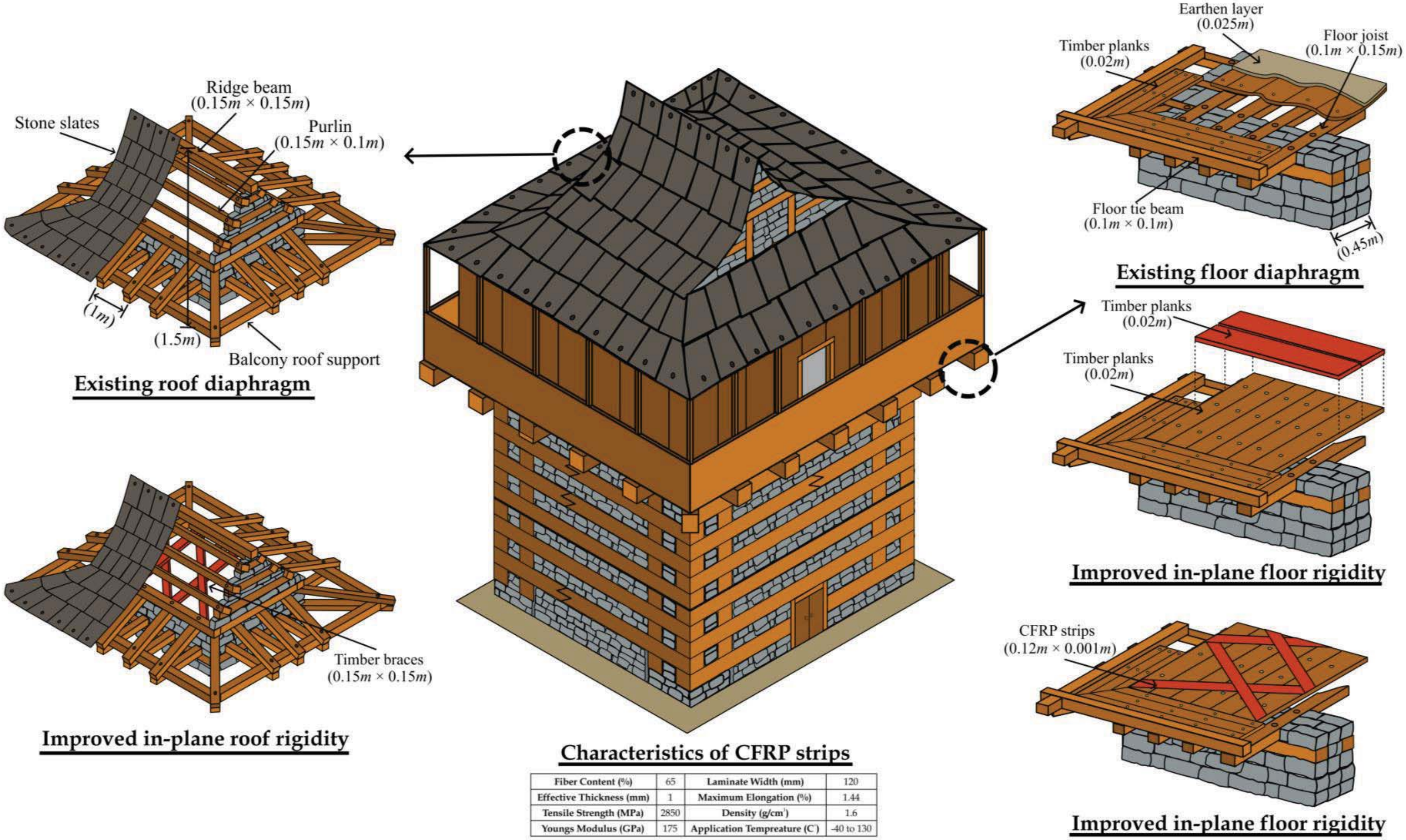
h_i = height of i^{th} story, l = length of building, w = width of building

Impact of observed features on earthquake-resilience

Features	Sub-Features	Tag
Siting	Flat ground	🟩
Architectural features	Plan	🟩
	Elevation	🟩
	Small horizontal projections	🟩
	Wall length	🟩
	Symmetry of wall/frame	🟩
	Placement of openings	🟩
	Number of openings	🟩
	Uniformity of story height	🟩
	Number of stories	🟩
	Gap between buildings	🟨
Structural features	Gravity/lateral load path	🟩
	Wall density	🟩
	Redundancy	🟩
	Roof weight	🟥
	Roof-to-wall/frame connection	🟩
	Wall/frame-to-foundation connection	🟥
	Wall-to-wall connections	🟩
	Roof connections	🟩
	Floor-to-wall connections	🟩
	Roof rigidity	🟥
	Floor rigidity	🟥
Soil condition and foundation	Soil condition	🟨
	Provision of plinth band	🟩
	Foundation size	🟩
Visual conditions	Visual condition	🟨
	Maintenance	🟨
	Material deterioration	🟨
Other	Seismic weight	🟥
	Damping	🟩
	Deformability	🟩

🟩 **Earthquake-resilient**
🟥 **Earthquake-vulnerable**
🟨 **Earthquake-resilient/vulnerable**

Figure 2.23: Summary of key features in Kath-kunni buildings



Characteristics of CFRP strips

Fiber Content (%)	65	Laminate Width (mm)	120
Effective Thickness (mm)	1	Maximum Elongation (%)	1.44
Tensile Strength (MPa)	2850	Density (g/cm^3)	1.6
Youngs Modulus (GPa)	175	Application Tempreature (C°)	-40 to 130

Figure 2.24: Suggested seismic safety measures for the Kath-kunni buildings

2.3 Thathara Buildings

2.3.1 Introduction

Thathara traditional construction practice is one of the most prevalent traditional building typologies observed in the 'Chamba' district of (Fig. 2.25) Himachal Pradesh, India. The word "Thathara" originated from the local terminology used for timber planks that are also used as the vertical load-carrying members (columns), locally referred to as 'Tholas.' This form of traditional building construction practice is prevalent and widely used by people of poor-to-middle socio-economic groups. It is mainly found in the high-altitude regions where timber was abundant at the time of their construction. In Thathara traditional construction practice, locally available rubble/semi-dressed stones (obtained from surrounding hills by breaking large rock masses into smaller pieces or from the stone quarries) and wood (specifically 'Deodar' wood, obtained by cutting trees) are used as the primary construction materials. Stone slates and sometimes timber planks are the material used to cover the roofs, and semi-dressed/random rubble stones are used in columns and walls. Timber elements are used in flooring, columns, bands, floor beams, roof supporting systems, and walls on the upper floors. Mud is used in many houses for plastering and as mortar in Thola. This construction practice is mainly adopted due to ease in the availability of the materials above in bulk in neighboring areas of Chamba.

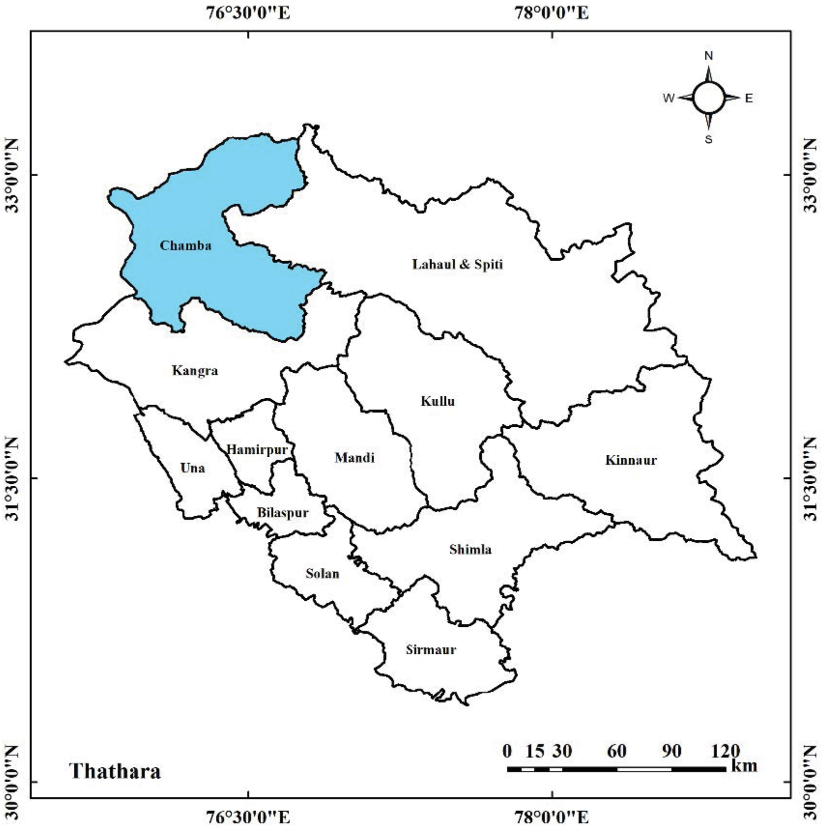


Figure 2.25: Map showing the regions of the prevalence of Thathara buildings

The field surveys conducted in the Chamba district revealed the existence of Thathara building typology on either side of the main roads on the Chamba-Bharmour-Hadsar Route, present in the villages of Palda, Sathli, Chamni, Saru, Paranghala, Sandhi, Hadsar and also in the villages of Kugti, Holi, and Mahoun on the Chamba-Khajjiar-Dalhousie-Bakloh-Lahru-Baduni route. All these regions where the Thathara traditional style of construction is observed fall in the Indian Seismic Zones IV/V as per India's current seismic zonation map (BIS 2016). The 'Thathara' style of residential construction has been in practice since more than 200 years ago, and some buildings even older than 100 years still exist in the study region. However, Thathara buildings are not constructed nowadays, mainly due to the scarcity of timber. The primary purpose of the Thathara style of traditional building construction practice is to provide shelter to human beings. Thus, it is mainly used for residential occupancy.

2.3.2 Siting

The siting of a building plays a crucial role in achieving adequate seismic performance. In general, flat site terrains are preferred for building construction due to frequent slope failure in the study region. However, it is not always possible to select flat landscapes due to the varying terrain present. Depending on the ground conditions, various structural configurations of Thathara buildings are seen during field surveys (Fig. 2.26). These structural configurations include flat ground configuration (Fig. 2.26(a)), a configuration with two largely different founding levels (Fig. 2.26(b)), building on sloped terrain ((Fig. 2.26(c)-(d)), configuration built on a raised dry-stone platform ((Fig. 2.26(e)) and the last configuration which is when the building is supported on Thola without any walls in the ground story in any of the directions (Fig. 2.26(f)). For Thathara buildings constructed on slopes, a slope gradient as high as 1:1 is observed (H: V; Fig. 2.26(c)).

2.3.3 Architectural Features

The Chamba district in Himachal Pradesh, where the Thathara style of construction is practiced, undergoes a cold climate in the winter between October to March and heavy precipitation in the rainy season between June to August. The impact of these climatic conditions is well reflected in the architecture of this style of construction, such as small door and window openings, a balcony on the upper floors to take sunbaths and to provide protection from rain and snow, wooden and mud interiors to maintain warm conditions within the building. The story height in the Thathara style of traditional construction has been significantly lesser than the modern contemporary constructions, which vary between 1.6-2.2 m (Fig. 2.27), with an average story height of 2.0 m. Usually, 2-stories are constructed in buildings resting over plane ground supported by artificially made platforms (by stacking stones of large size/creating a gravity retaining wall), whereas on steep slopes, these buildings have relatively smaller plan areas, and accordingly, buildings up to 4-stories can also be observed to fulfill single-family housing needs.

Thathara buildings are constructed following the basic principles of earthquake safety, maintaining regularity and symmetry in plans and elevations. Owing to this fact, Thathara buildings in the study region were mainly constructed and seen with rectangular plan shapes, keeping their plan aspect ratios between 1-2 (Fig. 2.28(a)-(b)). The oral rules still exist in the region of the prevalence of Thathara buildings for selecting the building plan dimensions. However, a few buildings with a selection of irregular plan shapes, such as L and T, were also seen (Fig. 2.28(c)-(d)), which are several decades old. Dry stone walls without mortar are used on the lowest floor to ensure the stability of the structure (Fig. 2.29(a)), whereas timber partitions are preferred on upper floors to reduce the seismic weight of the structure (Fig. 2.29(a)). These buildings are constructed with a balcony on the front side of the upper floors, whose width typically varies between 1.2-1.6 m, and it is supported by wooden posts or brick masonry columns on either side (Figs. 2.29(b)). The walls on the lower floors of Thathara buildings have low opening ratios, whereas the opening ratios significantly increase on the upper floors (Fig. 2.29). It is seen that many Thathara buildings have cupboards in the walls, and thereby, the thickness of walls reduces at those locations. Hence, to further strengthen the walls around those cupboards, the strengthening arrangements are similar to those seen in the Dhajji-Dewari style, i.e., diagonal braces around openings and cupboards could be seen frequently (Fig. 2.30).

(a) On flat ground (b) Two foundation level

(c) On sloping ground (d) On sloping ground

(e) On raised dry-stone platform (f) Supported on Thola without walls

Figure 2.26: Different siting observed in Thathara buildings

The lowest floor in Thathara buildings is used for cattle, whereas the upper floors are used as a temple or living space. The balconies are used for sunbathing and protecting the building occupants from rain. Besides these features, the use of 'Thola' (a peculiar combination of wooden planks with hand-packed stones, also plastered with mud at times) acting as a column offers the added benefit of relatively larger openings. Hence, Thathara-type buildings have a higher wall opening ratio than the other traditional building types prevalent in the region. Vertical projections were not observed (Fig. 2.29-2.31). In addition, Thathara buildings do not share common walls with adjacent buildings, and the distance between adjoining buildings can vary from a few centimeters to several meters (Fig. 2.32).

(a) Story height @ 1.60 m (b) Story height 2.0 m

Figure 2.27: Story heights in Thathara buildings

(a) Rectangular plan (b) Rectangular plan

(c) L-shaped plan (d) T-shaped plan

Figure 2.28: Plan shapes of Thathara buildings

(a) Small opening (b) Moderate opening

Figure 2.29: Openings in walls of Thathara buildings

(a) Diagonal bracings (b) Diagonal bracings

Figure 2.30: Cross-bracings around openings in walls of Thathara buildings

(a) Small projections (b) Small projections

Figure 2.31: Horizontal projections in Thathara buildings

(a) Isolated building (b) Sufficient gap

Figure 2.32: Distance between adjacent Thathara buildings

2.3.4 Structural Features

2.3.4.1 Load-bearing Wall-Frame Systems

The load-bearing system of Thathara buildings is identical to the 'Cribbage and Cator' traditional system found in the Himalayan belt (Bothara et al. 2022). The term 'Cator' is identical to the timber band, and the term 'Cribbage' is extra timber reinforcing in the corner region of the walls. The Thathara building system consists of cribbage locally called 'Thola' (a structural element identical to columns, which is either kept hollow or hand-packed with stones (Fig. 2.33) interconnected with floor beams and timber bands (Figs. 2.34) using timber nails. The lateral load resistance in Thathara construction is produced by the hybrid action of Tholas interconnected with timber beams (Fig. 2.34) and drystone walls without mortar. The typical cross-section size of Thola is observed to be 0.45 m × 0.45 m. However, in some cases, the size of Thola can be up to 0.60 m × 0.60 m. In the Thathara buildings, drystone walls (approximately 0.45 m thick, with their height-to-thickness ratios not exceeding 6) are used in the lowermost story, whereas 0.02 m thick timber planks are used as walls on the upper stories in most cases (Fig. 2.35(b)). A few Thathara buildings with dry stone walls continuing from the bottom to top stories were also observed (Fig. 2.34(a)). In Thathara buildings, where dry stone walls are used, intermediate timber bands are interconnected with the Thola using timber nails (Figs. 2.34(b)-(c)). Further, multiple timber elements from Thola run into the walls, up to a length of 0.3 m, providing Thola-to-wall connections (Fig. 2.34(a)). In many Thathara buildings, the mud mortar is plastered externally onto the internal and external faces of the drystone walls (Fig. 2.36) for insulation purposes. The typical sketch of the load-bearing system of Thathara buildings is shown in Fig. 2.37.

(a) Typical Cribbage (Thola)

(b) Thola width

(c) Thola depth

(d) Whole Thola

Figure 2.33: Thola in Thathara buildings

(a) Thola and bands

(b) Floor beam in Thathara buildings

(c) Thola-to-wall connections

(d) Thola and bands

Figure 2.34: Thola-to-wall connections in Thathara buildings

(a) Wall thickness @0.45m

(b) Wall thickness @0.45m

Figure 2.35: Wall thickness in Thathara buildings

(a) Mud plaster

(b) Cement plaster

Figure 2.36: Wall plasters in Thathara buildings

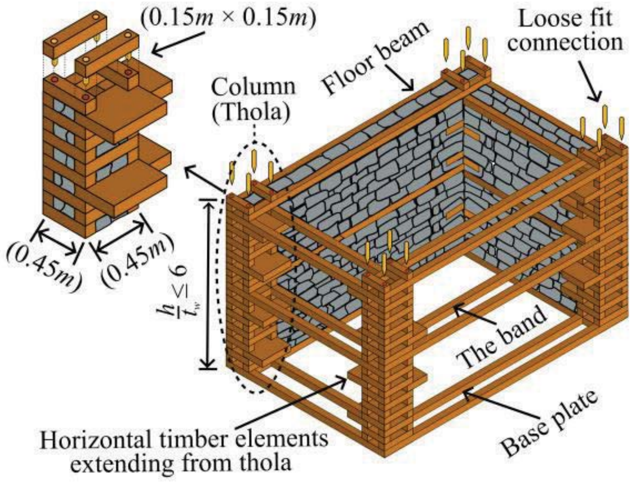


Figure 2.37: Typical sketch of the load-bearing system in Thathara buildings

2.3.4.2 Floor Systems

The details of the floor system in Thathara buildings are shown in Fig. 2.38. The floor system at the ground floor comprises the stone filling up to the plinth level, over which mud or a mixture of mud and cow dung is used to plaster and level the floor. In contrast, the floor system on the upper floor consists of timber planks on secondary beams resting over primary beams. In Thathara buildings, the secondary timber beams having a cross-section of 0.15 m × 0.15 m are spaced at 0.5 m (Fig. 2.38(a) and 2.39) on the primary timber beams of cross-section 0.20 m × 0.20 m spaced at 3.0 m (2.38(a) and 2.39). The connections between primary and secondary beams are achieved through nails. Timber planks of 0.02 m thickness are then nailed to secondary timber beams, with a thin overlay (approximately 0.025m) of the mud slurry placed to prevent direct timber exposure to fire and water (Figs. 2.38). In a few buildings, the use of plain cement concrete for flooring on the ground floor was also observed in Thathara buildings (Fig. 2.38(f)), though it is only a recent addition. No cross-planks are seen in Thathara buildings. Thus, the floor system of Thathara buildings is expected to behave as a flexible diaphragm.

2.3.4.3 Roof Geometry and Systems

The sloping roofs (either gable or hipped, sloping in the range of 15-25 degrees, Fig. 2.40(a)-(d)) is traditionally preferred in Thathara practices, primarily due to heavy rainfall and snowfall in the region of their prevalence. Stone slates are usually used to cover the roof system in traditional Thathara buildings. In a few cases, flat rigid RC roofs were also observed. The span of the roof truss varies between 3.60-6.00 m, whereas the rise of the roof truss varies between 0.60-1.20 m. In Thathara buildings, Tholas, located in the middle, are raised to the ridge level (Figs. 2.41 and 2.42) in the two opposite walls. The ridge beam (locally called 'Nhas') is directly placed over Tholas without connection. The rafters connected by the collar and tie beam (sometimes vertical posts are also seen to form a queen post arrangement of timber truss, Fig. 2.41) with c/c spacing of 1.2 m are connected at one end to the ridge beam with timber nails and at the other end to the wall plate (locally called 'Jail-Dal') through grooves. The wall plates are placed directly over the walls without any connection with the walls, although wall plates are connected with Thola at the ends. The rectangular-shaped purlins of cross-section 0.100 m × 0.075 m are spaced at 0.4 m and are nailed to the rafters at a spacing of 1.3 m. The stone slates are secured by connecting them to the purlins with iron nails.

(a) Primary and secondary floor beams (b) Primary and secondary floor beams

(c) Earthen cover in wooden floor (d) Earthen cover in wooden floor

(e) Wooden floor (f) Plain cement concrete floor

Figure 2.38: Floor systems in Thathara buildings

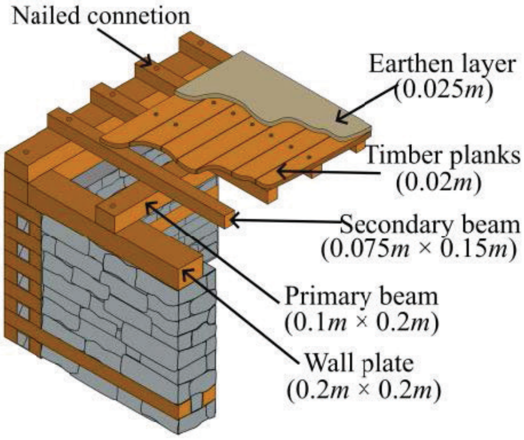


Figure 2.39: Typical sketch of the floor system in Thathara buildings

(a) Gable roof with stone slate

(b) Hipped roof with stone slate

(c) Cross gable roof with stone slate

(d) GI sheet as a roof

Figure 2.40: Roof geometry in Thathara buildings

(a) Trussed roof system

(b) Rafter-to-rafter connection

(c) Nhas with rafters spaced @ 1.2 m

(d) Nhas resting on Thola without any

Figure 2.41: Roof system in Thathara buildings

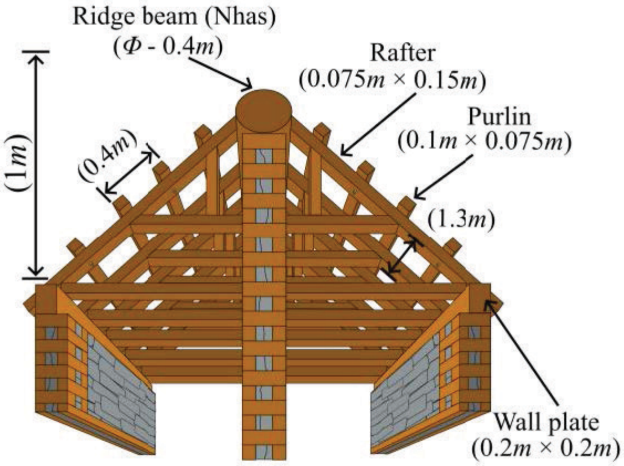


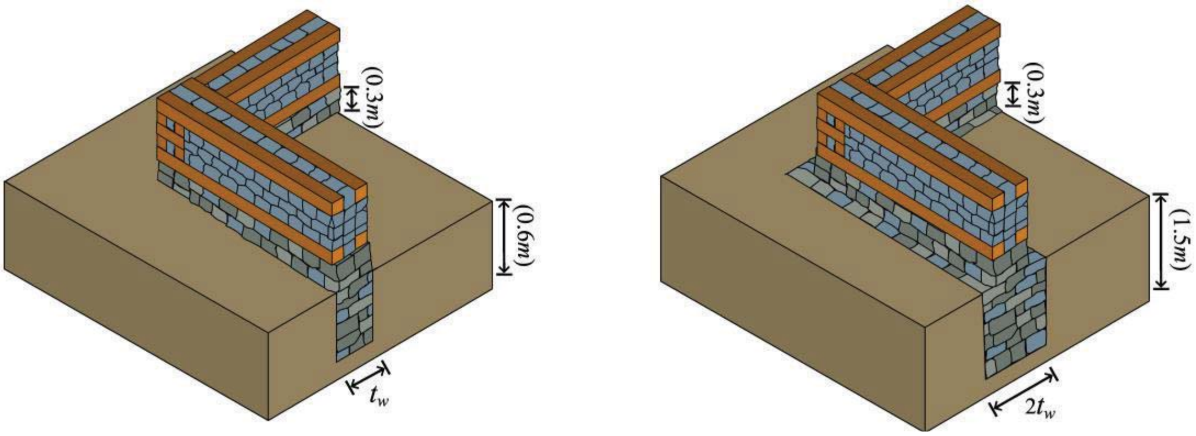
Figure 2.42: Typical sketch of the roof system in Thathara buildings

2.3.4.4 Soil Conditions and Foundations

The field/river stones are used in the construction of strip foundations in Thathara buildings (Fig. 2.43). The width of the foundation in this construction varies between 0.45–0.9 m. The depth of the foundation varies from building to building depending on the availability of the hard soil/rock strata, usually available in the regions at a shallow depth. Typically, the depth of the foundation varies between 0.6-1.5 m. The Tholas in 'Thathara' buildings directly rest on rubblestone strip footing, without any positive connection between Thola and the foundation.

(a) Stone foundation (b) Stone foundation

Figure 2.43: Foundations in Thathara buildings



(a) Foundation on hard soil (b) Foundation on soft soil

Figure 2.44: Typical sketches of foundations in Thathara buildings

2.3.5 Visual Conditions and Maintenance

During the field surveys, the visual conditions of many Thathara buildings were observed to be in the range of average to good, whereas some buildings were found to be severely damaged and unoccupied (Fig. 2.45) in Kugti Village, highlighting a paradigm shift in building construction practices from the traditional ones to their contemporary counterparts. The Thathara buildings are maintained by owners. The building occupants revealed that Thathara buildings are expected to perform fairly well for a life span of ~70-80 years, without any excessive maintenance costs, due to the use of highly durable materials (i.e., semi-dressed stones, stone slates, and Deodar wood). The minor interventions that are required frequently in Thathara buildings include the repointing of mud plaster in washed areas due to rain, and significant interventions for maintenance require the replacement of timber elements, particularly in the roofs.

(a) Deteriorated building

(b) Deteriorated building

Figure 2.45: Deteriorated Thathara buildings in the study region

2.3.6 Contemporary Modifications

The occupants of Thathara buildings revealed that the construction scenario in the region had changed significantly in the past few decades. Nowadays, contemporary construction practices such as using flat RC roofs and burnt clay bricks can be seen frequently seen in and around the region of the prevalence of Thathara construction. Several contemporary construction practices can be seen in the Thathara construction (Fig. 2.46). The practices include using burnt clay bricks to construct walls (Fig. 2.46(a)). The use of steel sections in the roof supporting system (Fig. 2.46(b)), brick columns (Fig. 2.46(c)), and RC rigid roofs can also be seen in Thathara construction. Most of these contemporary modifications are the forced change in this construction style due to the lack of timber required for such construction and the unavailability of skilled artisans knowing Thathara construction.

2.3.7 Past Seismic Performance and Vulnerability

The investigations conducted in this study suggest the origin of the Thathara construction at least 3-4 centuries before the present time. However, the exact age of these buildings is unknown. One of the reports (Hughes 2000) suggests the existence of this construction in Northern Pakistan about 1000 years ago. The Himalayan region where Thathara buildings are prevalent faced several strong earthquakes in the past few centuries. A few of these earthquakes include the 1720 Kumaun earthquake (M>8), the 1803 Garhwal earthquake (Mw=8.1), the 1897 Assam earthquake (Mw=8.1), the 1905 Kangra earthquake (Mw=7.8), the 1934 Bihar Nepal earthquake (Ms=8.1), the 1950 Assam earthquake (M=8.6), the 1975 Kinnaur earthquake (Ms=6.8), the 1991 Uttarkashi earthquake (Mw=6.8) and the 1999 Chamoli earthquake (Mw=6.6). When asked about the performance of the Thathara buildings, the occupants recollected and replied that no damage was observed in Thathara buildings under the recent earthquakes (those that have occurred in the past 3-4 decades). Many of these Thathara buildings are standing as it is from the past century, and no past damage has been reported specific to Thathara buildings. These facts highlight that these buildings have performed well under several earthquakes compared to other regional building practices.

Though these Thathara buildings survived several past earthquakes, there are a few specific features of these Thathara buildings that add to their seismic vulnerability. The siting and architectural features that add to their seismic vulnerability are selecting sites with steep slopes, leading to severe irregularities in the buildings, sometimes selecting complex plan shapes (e.g., T-shape), and the inadequate gap between two buildings. The structural features that further add to their seismic vulnerability are the absence of connections between the wall plate and wall, and between the ridge beam and Thola. The use of thicker walls made of stones and stone slates as roofing further makes them heavy-weight constructions resulting in higher earthquake force demands on them. Due to the limited in-plane rigidity of timber planks and the absence of cross-bracings in the roofs, both the floor and roof systems of Thathara buildings behave as flexible diaphragms; hence walls in Thathara buildings are not fully restrained against out-of-plane movements.

2.3.8 Earthquake-Resilient Features

Thathara buildings possess several earthquake-resilient characteristics in their siting, architectural, and structural features shown in Fig. 2.47. Starting from the site selection, it is usual practice to construct these buildings on flat terrain. As a result, these buildings are regular in shape in both plan and elevation. The plan dimensions of the Thathara buildings are chosen to result in a plan shape that is rectangular shape with a plan aspect ratio not exceeding 2. Smaller story heights and total building height ensure a low height-to-width ratio for these buildings. These buildings are further characterized by very small sizes of door and window openings, along with diagonal bracings around the openings (near cupboards) to strengthen the walls. The upper portions of these buildings are timber heavy construction, which reduces the seismic weight of the building, minimizes the overturning effects, and provides overall stability to these buildings. Many of these buildings are constructed in isolation, whereas some are also seen in close proximities (gaps of 0.10 m or less). Thus, the possibility of pounding cannot be ignored entirely in Thathara buildings.

The high wall thickness and small story heights ensure the slenderness ratio of walls, typically below 6, and prevent out-of-plane overturning of walls. The interconnected timber bands at the plinth, lintel, and floor level provide the wall-to-wall connections and extra reinforcing at the corners through cribbage, further preventing vertical cracking. Additionally, multiple timber elements are extended from Thola-to-wall up to certain lengths to provide Thola-to-wall connections. The floor systems in Thathara buildings comprise primary and secondary beams, which are inter-connected, and the primary beams are also connected with wall plates. The roof system in Thathara buildings has well-nailed rafter-to-rafter connections. In many cases, the gable end of walls is filled with thin (lightweight) timber planks and a gable band. Thus, failure of the gable end is also prevented in Thathara buildings.

(a) Burnt clay brick walls (b) Structural steel sections

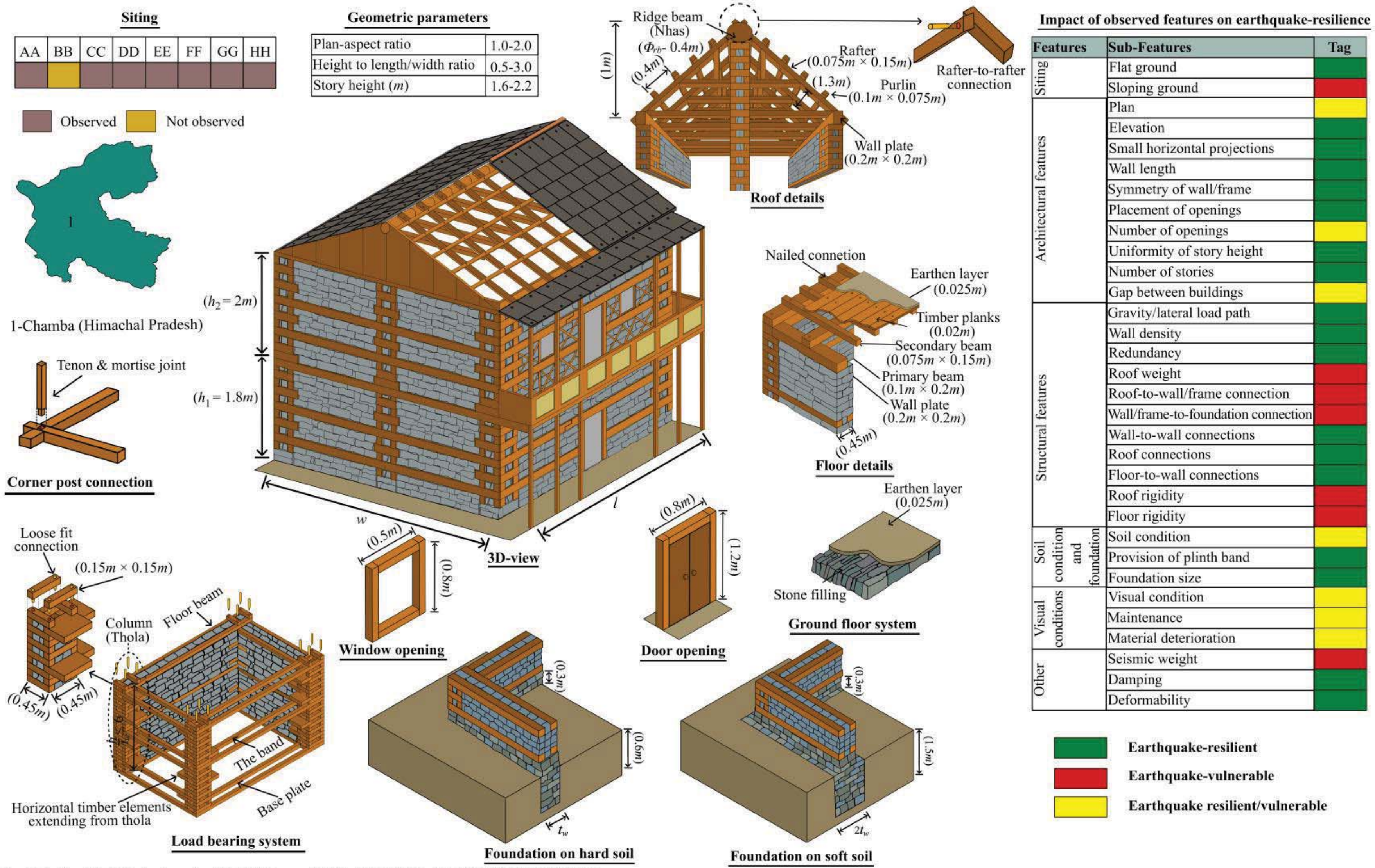
(c) Brick column (d) CGI sheets on the roof

Figure 2.46: Influence of contemporary materials on Thathara buildings

Apart from these siting, architectural, and structural features, Thathara buildings possess other important characteristics related to their construction materials and connections that are very beneficial for their enhanced earthquake resistance. The stones filled in between timber beams at the floor level and timber bands in the middle of the story, in Thathara buildings, led to the following important actions: (i) timber bands along with stones provide the shear resistance and deformability to the Thathara buildings, and thus, increased energy dissipation capacity, and (ii) the timber and stones in walls of Thathara buildings develop good frictional resistance and possess high damping ratio (10% of the critical damping in the undamaged state, Bothara et al. 2019; Bothara et al. 2022) as compared to contemporary materials (e.g., reinforced-concrete, where it is 5% of the critical damping in the undamaged state). The high damping ratio reduces the seismic force demands on Thathara buildings. The other important features of Thathara buildings are 'loose-fit' (semi-flexible) connections of the components of Thola (cribbage), Thola-to-wall, timber band-to-Thola allow the deformations in the building and various components in a controlled manner.

2.3.9 Suggested Seismic Safety Measures

As discussed in the previous section, the Thathara building lacks connections between the wall plate and wall, the wall-plate-to-Thola, and between the ridge beam and Thola. These connections can be further improved using additional timber boards and connecting them with the existing structure, as shown in Fig. 2.48. The ridge beam can also be connected with Thola using timber boards and metal strips (Fig. 2.48). The floors and roofs of the Thathara buildings are expected to behave as flexible diaphragms. Therefore, to improve the in-plane rigidity of the floors and roofs, the necessary measures for the Thathara buildings are suggested and shown in Fig. 2.48. Further, new Thathara buildings in the region are not constructed; hence, the suggested safety measures apply to the existing Thathara buildings. The in-plane rigidity of the floor system of Thathara buildings can be improved either by providing and nailing additional timber planks perpendicular to the existing timber planks, cross-timber planks or by providing carbon fiber reinforced polymer (CFRP) straps using epoxy diagonally (adapted from Gattesco and Macorini 2014) as shown in Fig.2.48. Further, to improve the rigidity of the roof system in Thathara buildings, timber/metal diagonal bracings can be added and connected to the roof. The seismic weight of roofing can also be reduced using lightweight roofing (e.g., CGI sheets). However, these roof coverings may be less durable and require frequent replacement.



Siting

AA	BB	CC	DD	EE	FF	GG	HH
🟫	🟨	🟫	🟫	🟫	🟫	🟫	🟫

🟫 Observed 🟨 Not observed

Geometric parameters

Plan-aspect ratio	1.0-2.0
Height to length/width ratio	0.5-3.0
Story height (*m*)	1.6-2.2

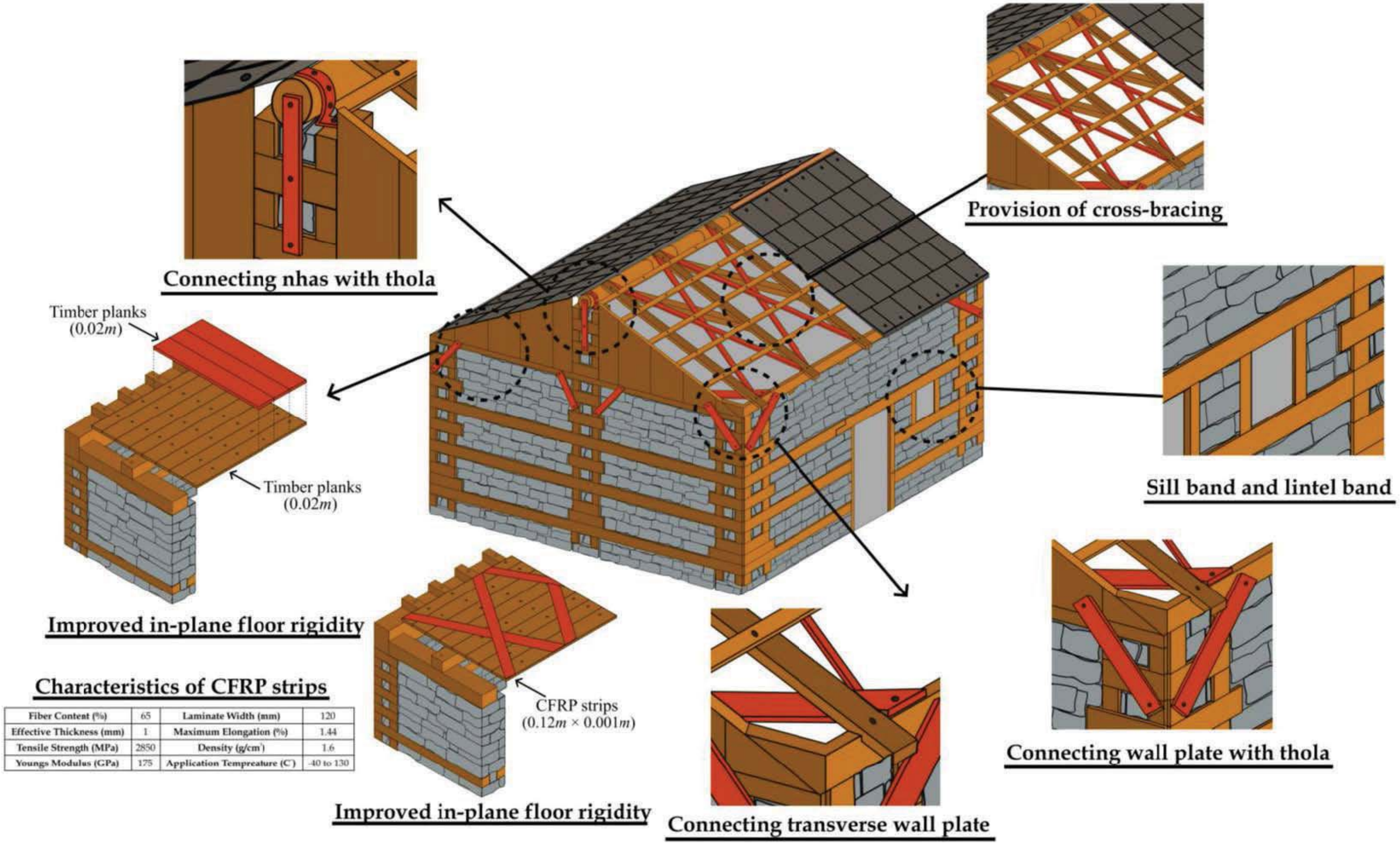
Impact of observed features on earthquake-resilience

Features	Sub-Features	Tag
Siting	Flat ground	🟩
	Sloping ground	🟥
Architectural features	Plan	🟨
	Elevation	🟩
	Small horizontal projections	🟩
	Wall length	🟩
	Symmetry of wall/frame	🟩
	Placement of openings	🟩
	Number of openings	🟨
	Uniformity of story height	🟩
	Number of stories	🟩
	Gap between buildings	🟨
Structural features	Gravity/lateral load path	🟩
	Wall density	🟩
	Redundancy	🟩
	Roof weight	🟥
	Roof-to-wall/frame connection	🟥
	Wall/frame-to-foundation connection	🟥
	Wall-to-wall connections	🟩
	Roof connections	🟩
	Floor-to-wall connections	🟩
	Roof rigidity	🟥
	Floor rigidity	🟥
Soil condition and foundation	Soil condition	🟨
	Provision of plinth band	🟩
	Foundation size	🟩
Visual conditions	Visual condition	🟨
	Maintenance	🟨
	Material deterioration	🟨
Other	Seismic weight	🟥
	Damping	🟩
	Deformability	🟩

🟩 **Earthquake-resilient**
🟥 **Earthquake-vulnerable**
🟨 **Earthquake resilient/vulnerable**

h_i= Height of i^{th} story, l = Length of building, w = Width of building , Φ_{rb}= Diameter of ridge beam

Figure 2.47: Summary of key features in Thathara buildings



Characteristics of CFRP strips

Fiber Content (%)	65	Laminate Width (mm)	120
Effective Thickness (mm)	1	Maximum Elongation (%)	1.44
Tensile Strength (MPa)	2850	Density (g/cm^3)	1.6
Youngs Modulus (GPa)	175	Application Tempreature (C°)	-40 to 130

Figure 2.48: Suggested seismic safety measures for Thathara buildings

2.4 Dhajji-Dewari Buildings

2.4.1 Introduction

The term Dhajji-Dewari is derived from the Persian language meaning 'Patchwork Quilt Wall' and it is a traditional building practice of the Western Himalayan region. In particular, these buildings can be seen in the union territory of Jammu and Kashmir and a few buildings also in the city of Shimla and nearby areas in the state of Himachal Pradesh, India (Fig. 2.49). A similar building typology is found in various countries (e.g., Portugal and other Eastern European countries) as well, though they are known by different names. This form of traditional building practice is very popular and widely used by people of low-to-middle socio-economic levels, and is found in both plain and high-altitude regions. The traditional Dhajji-Dewari buildings have a high service life as compared to the other building practices in the region of their existence. Some buildings as old as ~200 years or more are still in existence in Srinagar city. They are found in both rural and urban areas, occupied by large families.

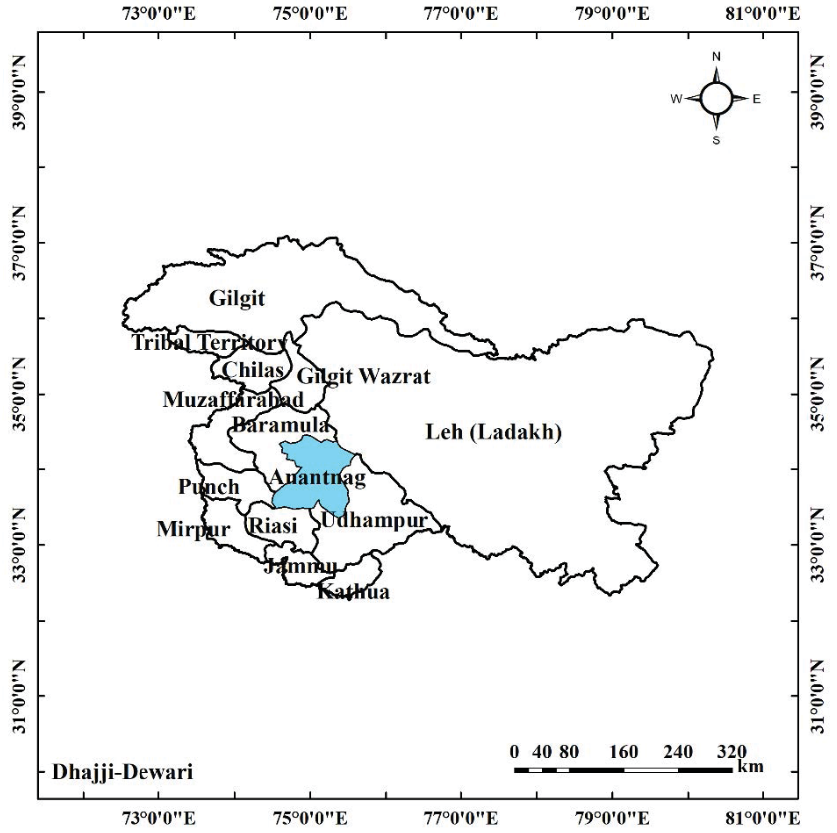


Figure 2.49: Map showing the regions of the prevalence of the Dhajji-Dewari buildings

In the Western Himalayan region, Dhajji-Dewari buildings are extensively known for their low cost and speedy construction by utilizing locally available natural construction materials. The usage of good quality timber and good craftsmanship skills can provide proper detailing that can offer resistance to seismic forces. In comparison to modern construction, builders need not be dependent on manufacturers for materials used in Dhajji-Dewari buildings, as the materials can be chosen by themselves. Dhajji buildings have superior thermal performance when compared to the other contemporary building typologies, and therefore a preferred choice for rich merchants and politicians. Dhajji-Dewari buildings most commonly consist of a timber frame (which may or may not be braced), where the spaces available between the frame/bracings are filled with a thin wall usually made up of stone or brick masonry, traditionally laid in mud mortar, to create a patchwork of minimal masonry panels. The walls of Dhajji-Dewari buildings are generally plastered in mud mortar. The discussions with homeowners suggest that Chir Pine, Kail, and Deodar timber is mostly used for horizontal, vertical, and bracing members in Dhajji-Dewari construction and locally available bricks/stones are used to infill the walls with mud that is used as mortar for binding purposes.

2.4.2 Siting

Dhajji-Dewari buildings can be found on both (i) flat ground (Fig. 2.50(a)) and (ii) sloping terrain conditions (Fig. 2.50(b)). When located on slopes, an artificial platform is created to attain a flat platform for the building to rest on. The typical photographs showing siting features of Dhajji-Dewari buildings that were captured during field surveys are shown in Fig. 2.50. When sloping terrains are encountered, constructing back walls to retain soil is also seen in some Dhajji-Dewari buildings.

(a) On flat ground (b) On sloped terrain

Figure 2.50: Different siting observed in Dhajji–Dewari buildings

2.4.3 Architectural Features

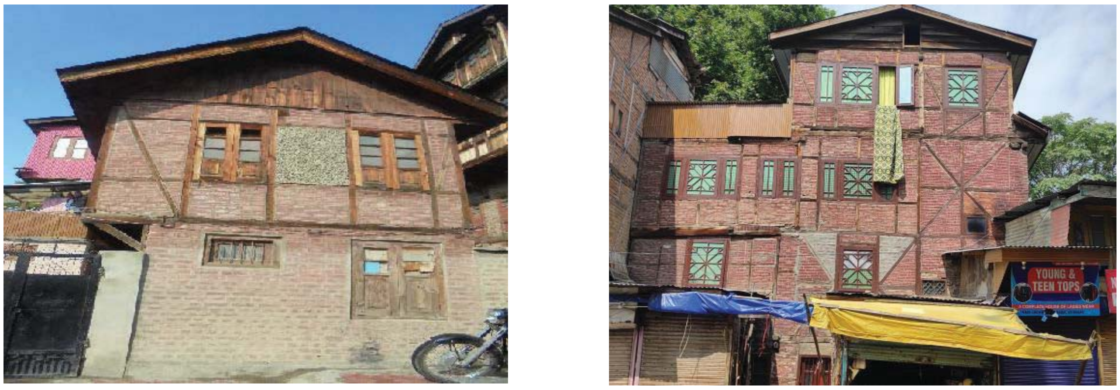
The main purpose of the Dhajji-Dewari style of traditional building construction practice is to provide shelter to human beings. Thus, it is mostly used for residential occupancy (Fig. 2.51). However, this traditional style of construction can also be seen in hospitals as well as buildings with residential and commercial occupancies (Fig. 2.51). In general, Dhajji-Dewari buildings are constructed following the principles of earthquake safety by maintaining symmetry and regularity in their plan and elevation. Dhajji buildings are mostly rectangular in plan (Fig.2.52), with a few exceptions, where complex plan shapes are also seen. The typical plan aspect ratio of the Dhajji building varies from 1-3. The typical plan dimensions of Dhajji buildings have lengths in the range of 10-15 m, and widths in the range of 5-15 m. Dhajji-Dewari buildings are seen up to 4 stories with the typical story heights varying between 2.5-3.2 m (Fig. 2.52). The single-storied buildings are found in rural areas, whereas multi-storied buildings are prevalent in urban areas, e.g., Srinagar city. In rural areas, the lowest floor levels are used to shelter livestock, while in urban areas; it is used as a normal townhouse/shop. Dhajji-Dewari buildings have well-distributed openings in two directions, which typically range between 20%-30% of the length of the walls. The photographed images of the Dhajji building with varying openings are shown in Fig. 2.54. In addition, if these buildings are constructed on sloping terrain, the openings are mainly concentrated on the downhill side of the building which covers approximately 50% of the length of the walls (Fig. 2.53). The alignment of openings is usually uniform in Dhajji-buildings resting on flat ground. In most of the Dhajji buildings, large rooms exist to conduct social gatherings. Large rooms are mostly constructed in the upper story of buildings, essentially called halls with a typical span of 8-10 m. The horizontal projections in Dhajji buildings vary between 1.5-1.8 m (Fig. 2.55). Dhajji buildings are usually constructed in isolation in rural areas. However, in the case of extended buildings, the walls can be shared and many Dhajji-Dewari buildings in the Srinagar downtown area are constructed in rows, sometimes without any gaps between them (Fig. 2.56).

(a) Hospital building (b) Residential-commercial building

Figure 2.51: Different occupancies in Dhajji–Dewari buildings

(a) Rectangular plan shape (b) Complex plan shape

Figure 2.52: Plan shapes in Dhajji–Dewari buildings

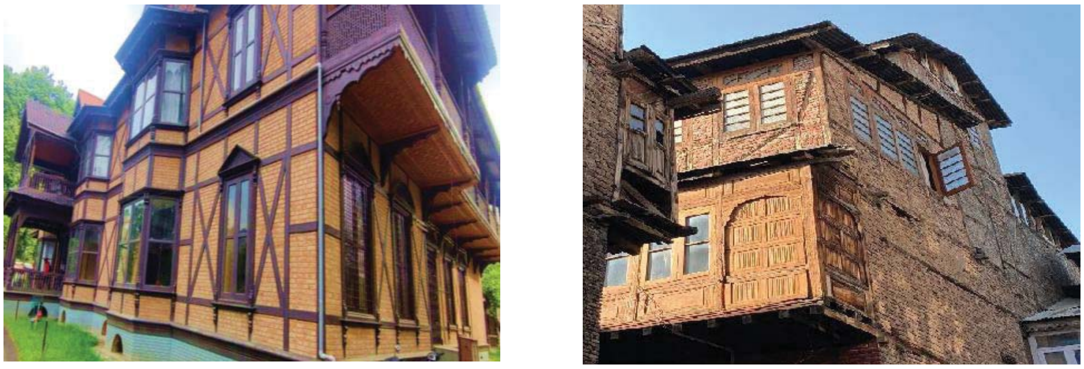


(a) Story height @ 3.0 m (b) Story height @ 3.0 m

Figure 2.53: Story heights in Dhajji-Dewari buildings

(a) Moderate openings (b) Large openings

Figure 2.54: Openings in Dhajji-Dewari buildings



(a) Small projections (b) Moderate projections

Figure 2.55: Horizontal projections in Dhajji-Dewari buildings

(a) Closely spaced buildings (b) Buildings with a gap of 0.1 m

Figure 2.56: Distance between adjacent Dhajji-Dewari buildings

2.4.4 Structural Features

2.4.4.1 Load-bearing Wall-Frame Systems

The Dhajji-Dewari traditional form of construction is also referred to as "Brick-nogged timber frame construction" in the Indian standard (BIS 1993a). Timber framing and bracings (if any) form the major structural system for Dhajji-Dewari buildings. A two-step procedure is used in the construction of Dhajji-Dewari buildings. Firstly, the timber frame is constructed and secondly, the spaces in between the frames are filled with brick/stone masonry traditionally laid using mud mortar. As a result, the brick/stone masonry does not carry any direct vertical loads in Dhajji-Dewari buildings. This specific feature permits the construction of Dhajji-Dewari buildings with relatively thinner walls, and accordingly, the wall thickness in the Dhajji-Dewari buildings typically varies between 0.11-0.23 m. The wall density in this construction is typically low as compared to the other traditional practices of the Himalayan region and it ranges from 10-15%. A good and equal distribution of walls exists in Dhajji-Dewari buildings in two orthogonal directions.

The structural members used in the typical timber frame of a Dhajji-Dewari building include (i) vertical studs, (ii) horizontal members (top plate, bottom plate, and intermediate horizontal posts), and (iii) bracings. The typical cross-sectional dimensions of the vertical studs usually vary between 0.05 m × 0.10 m to 0.10 m × 0.10 m. In the case of horizontal members, the dimensions are 0.04 m × 0.10 m, and in the case of diagonal bracings, the dimensions are 0.10 m × 0.025 m. The dimensions of the top plate and base plates are 0.10 m × 0.10 m. A variety of connections/joints (lap joint, scarf joint, and tenon and mortise joint) are seen and used to connect the different members for the effectiveness of this structural system (Fig. 2.57). The buildings in which the top plate or bottom plate runs for a greater length, the horizontal plates are connected by lap/scarf joints and the corner posts are joined by quarter or half-tenon connections (Fig. 2.57). The vertical posts (vertical studs) are connected to the top and bottom plate using three different types of tenon and mortise joint connections (Fig. 2.57). These connections are further nailed using nails of 4.55 mm diameter that are approximately 0.075 m long. The connection details of horizontal studs differ from the vertical posts. Two different types of connections are used in horizontal studs. The bracings are connected at the corners using nails of diameter 3.5 mm that are 0.05 m long. The vertical studs consist of main posts and intermediate posts sized 0.05 m × 0.10 m and 0.04 m × 0.09 m, respectively. The number of main posts increases in the case of buildings with greater length. The typical details of these members are shown in Fig. 2.57. These vertical studs and horizontal members help in dividing the masonry infills into small horizontal and vertical parts, imparting strength and preventing the out-of-plane failure mode of stone/brick masonry walls. Mostly, the walls of the Dhajji-Dewari building aren't plastered but, in a few buildings, plastering of walls is done.

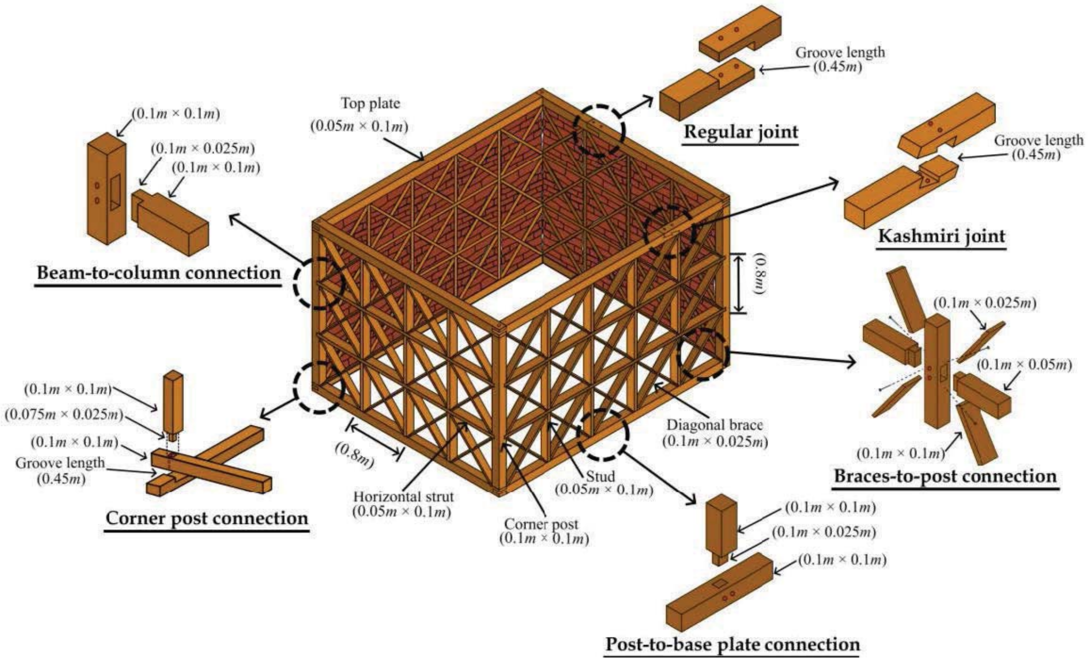


Figure 2.57: Typical sketch of the load-bearing system of Dhajji-Dewari buildings

A variety of bracing patterns are observed in Dhajji-Dewari buildings. These bracing patterns vary from random subdivisions of a wall to highly regular orientations in some of the buildings (Fig. 2.58). No specific reasons are mentioned to choose different bracing patterns but primarily the choice is jointly governed by the carpenter and the owner. The infill for walls is made of rubble or cut stone or bricks in mud mortar. Additional strength for mud mortar is imparted by adding lime to it. The ratio of stone to mud mortar by volume in walls of Dhajji buildings typically ranges from 1:8-1:10 and a majority of stones used in infill walls are of size up to 0.075 m with their gaps filled by smaller sized stones.

(a) No bracing (b) X-bracing

(c) Mixed bracing (d) Mixed bracing

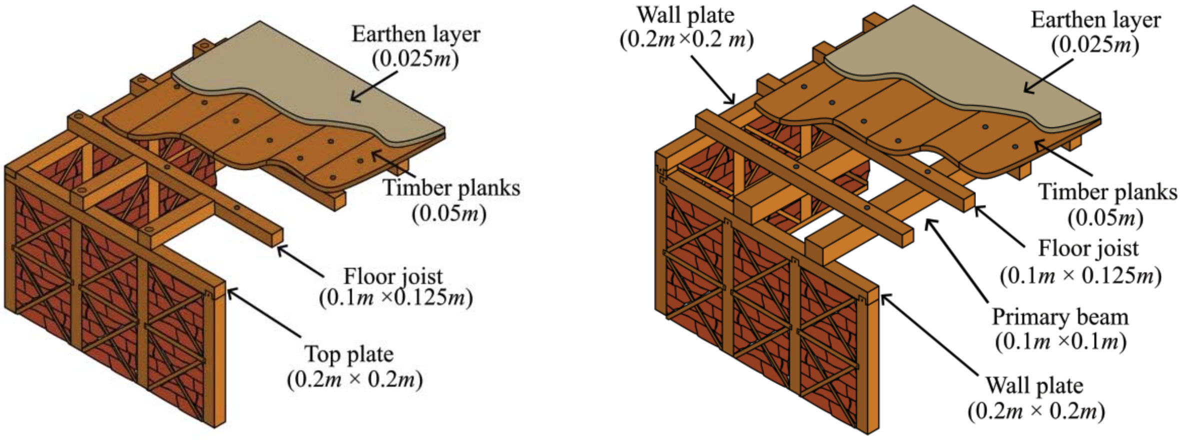
Figure 2.58: Bracing patterns in Dhajji-Dewari buildings

2.4.4.2 Floor Systems

Different floor systems are employed in Dhajji-Dewari buildings on the ground floor and upper floors. The ground floor usually consists of stone filling overlaid with mud flooring. The typical upper floor system in Dhajji-Dewari buildings consists of timber planks resting over the floor joists (Fig. 2.59). The vertical posts are connected by the primary timber beams (horizontal posts) and the distance between timber posts was observed to be 1 m. The floor joists span between the primary timber beams with timber planks nailed to the floor joists. The other possibility could be the case when the timber planks are nailed to the secondary beams that are supported by primary beams (Fig 2.59). The floor joists present at the extreme ends of the floor system are connected by lateral elements that are either nailed or connected by C-type joints along both the length and width of the floor system as shown in Fig. 2.60. The distance between floor joists varies in the range of 0.4-0.6 m. In the case of lesser distant vertical posts (less than 0.6 m), the floor joists are connected on top of vertical posts with the help of GI straps or through tenon and mortise joints. In most cases, the floor joists are simply nailed to reduce labor costs. Floor joists provided at intermediate locations between vertical posts were also observed during the field survey (in the case of buildings with the distance between vertical posts being greater than 0.6 m). The typical dimensions of the top plate, primary beams, floor joists, and floorboards are shown in Fig. 2.60. The timber floors are provided with a mud overlain which serves the following purposes: (i) the primary purpose of leveling the floor; and (ii) the secondary purpose of protecting the floors from fire. Cross-planks or any other arrangements are not seen in the floor system, and thus, the floor system in Dhajji-Dewari buildings is expected to behave as a flexible diaphragm.

(a) Primary and secondary beams (b) Primary and secondary beams

Figure 2.59: Floor system in Dhajji-Dewari buildings



(a) (b)

Figure 2.60: Typical sketch of the floor system in Dhajji-Dewari buildings

2.4.4.3 Roof Geometry and Systems

The roof system typically spans between 4-12 m in Dhajji-Dewari buildings and consists of timber trusses with corrugated galvanized iron sheets (Fig. 2.61). The roof system typically consists of timber trusses spanning between principal timber columns or on primary beams (Fig. 2.62). The timber trusses are arranged to form a gable/hipped roof configuration which offers protection from severe weather conditions. There were two types of roof systems observed during the survey. In the first case with the roof's span length of less than 6 m, shorter king posts of dimension 0.1 m × 0.1 m are provided along with lateral boards or struts of dimension 0.1 m × 0.1 m are provided. In the second case with the roof's span length greater than 6 m, longer king posts (0.1 m × 0.1 m), queen posts (0.1 m × 0.1 m), and lateral boards or struts (0.1 m × 0.1 m) are provided. The rafters and purlins are generally spaced at a distance of 1.2 m and 0.3 m, respectively. The rafter, tie beam, and top plate are connected by tenon and mortise joints and are additionally tied using GI straps. The GI straps are nailed in place to hold all the elements together. Rafter-to-rafter connections are established through lap joints. Hipped roofs are preferred as they have better stiffness properties compared to roofs with gable ends. No in-plane bracings were observed in the timber trusses. The typical sketch of the roof system of Dhajji buildings is shown in Fig. 2.62.

(a) Roofing members (b) Queen post roof truss

Figure 2.61: Roof system observed in Dhajji–Dewari buildings

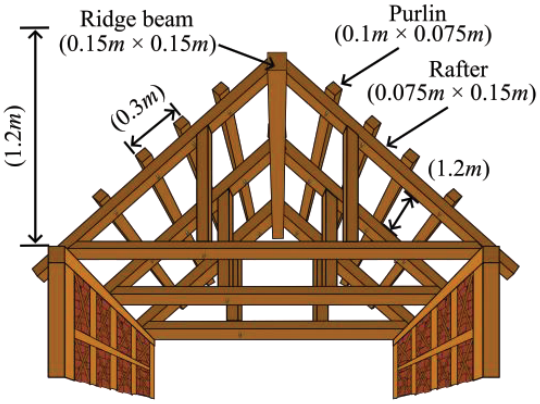


Figure 2.62: Typical sketch of the roof system in Dhajji–Dewari buildings

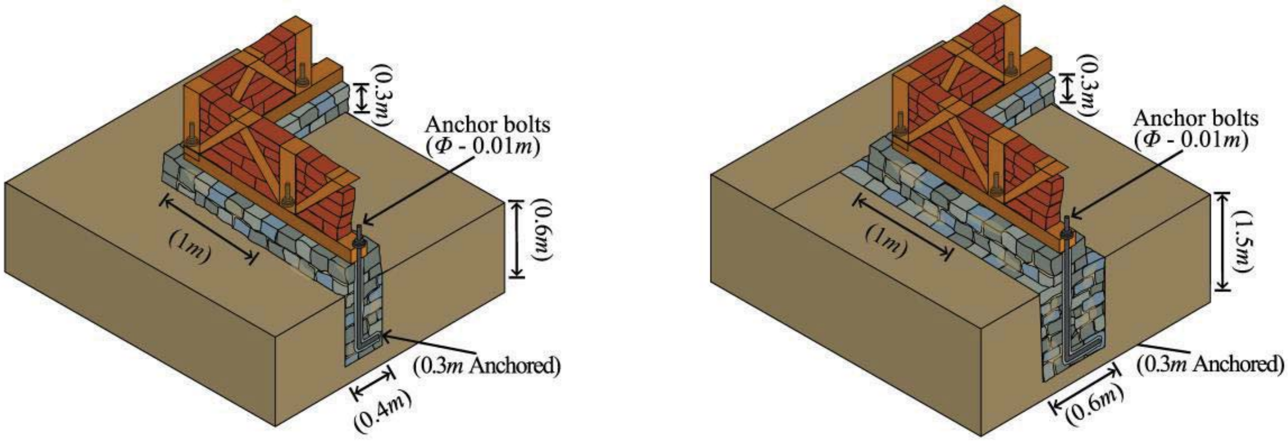
2.4.4.4 Soil Conditions and Foundations

Typically, Dhajji-Dewari buildings have shallow foundations made up of rubble/field stone strip footing, with the provision of drainage around the timber frame. The depth and width of the foundation vary based on both building and location specifications but Typically, the depth of the foundation in Dhajji buildings is 0.4-0.6 m and the width of the foundation varies between 0.6-1.8 m, depending on the soil strata and the number of stories. Dhajji-Dewari buildings mostly rest on soft soil that is prevalent in and around Srinagar. Nominally reinforced-concrete foundations are also used in recent constructions since the 2005 Kashmir earthquake. At times, the superstructure of Dhajji-Dewari buildings is constructed before site planning. Dhajji-Dewari buildings are generally raised on the stone platform from ground level to prevent the deterioration of timber due to water. The height of the raised stone platform usually depends on the site location and can typically range from 0.5-2.0 m, above the ground level. Although there exists no evidence, the survey shows that previous bolting of foundation existed at some point in time. Traditionally, no anchorage was provided between the foundation and structure. However, post the 2005 Kashmir earthquake, bolts are used to anchor the structure to the foundation (Fig. 2.63). The base plate also called as plinth beam of Dhajji buildings is connected by lap/scarf joints.

(a) Bolting of plinth beam to foundation

(b) Provision of anchor bolts in the foundation

Figure 2.63: Foundations of Dhajji-Dewari buildings



(a) Foundation on hard soil

(b) Foundation on soft soil

Figure 2.64: Typical sketches of foundations in Dhajji-Dewari buildings

2.4.5 Visual Conditions and Maintenance

Most of the Dhajji-Dewari buildings are well-maintained. At times, Dhajji-Dewari buildings are planned for a short period (temporary structure), hence proper care is not taken which leads to the deterioration of timber as shown in Fig. 2.65. Timber is environmentally safe and durable, therefore using timber for a short period cannot be justified. During the survey, it was observed that, in a few buildings, brick infills had been damaged and a few timber members had degraded. A well-planned Dhajji-Dewari building, protected from external factors such as moisture can sustain for longer years. In case of the absence of a retaining wall or plinth level, capillary action takes place causing severe degradation in timber. The same observation can be noticed when poor-quality timber is used without any preservatives to protect the timber. Overall, the maintenance of Dhajji-Dewari buildings is good to average.

2.4.6 Contemporary Modifications

Nowadays, a few practices from contemporary constructions can also be seen in the Dhajji-Dewari construction or vice-versa (Fig. 2.66). RC columns and the usage of burnt brick clays as infill materials are seen as part of the contemporary modifications in several areas.

(a) Deterorated timber (b) Damaged infill walls

Figure 2.65: Deteriorated Dhajji buildings in the study region

(a) Burnt clay bricks

Figure 2.66: Influence of contemporary materials in Dhajji-Dewari buildings

2.4.7 Past Seismic Performance and Vulnerability

The investigations conducted in this study suggest the origin of the Dhajji-Dewari construction at least 3-4 centuries before the present time. However, the exact age of these buildings is unknown. The Himalayan region where Dhajji-Dewari buildings are prevalent faced several multiple strong earthquakes in the past few centuries. However, there are limited past damage reports which specifically talk about the seismic performance of Dhajji-Dewari buildings. During the 1967 Kashmir earthquake (Mw=5.5) Dhajji buildings up to 5-story survived without any damage due to energy dissipation caused by friction of masonry infill walls against timber frame (Gosain and Arya 1967). More recently, it was the 2005 Kashmir earthquake (Mw=7.6), that showed its excellent seismic performance, even though the region suffered extensive damage to the other building types. When asked about the performance of the Dhajji-Dewari buildings the occupants recollected that during the Kashmir earthquake, Dhajji-Dewari buildings performed very well with no to little damage as compared to the other buildings. Langenbach (2005) reported the evidence of earthquake damage was limited to hairline cracks in the plaster over Dhajji-Dewari walls where the infill masonry walls contacted the timber. Larger cracks could be found on the inside face of the exterior and party walls with the neighboring house at the corner of the stairway. None of these cracks indicated a threat to the stability of the building. Similarly, Rai and Murthy (2006) reported no to very little damage to Dhajji-Dewari buildings during the 2005 Kashmir earthquake. No collapse has been observed for such masonry even in the areas of higher shaking. There are specific reports from India as well as other countries which showed that under strong past earthquakes, the timber frame buildings survived whereas the other structural systems collapsed (Fig. 2.67).

The few specific features that could add to the seismic vulnerability of Dhajji-Dewari buildings include the concentration of openings provided only on one side of the walls can induce torsion in buildings during earthquakes. The large spacings between posts can reduce the confining action of the frame to the stone/brick walls and uneven placement of bracings can further increase their seismic vulnerability. In recent forms of Dhajji-Dewari construction, nails are used in the timber frame which stiffens the frame leading to the attraction of relatively larger seismic forces. Further, the timber planks are nailed to floor joists, thus, they offer very limited in-plane stiffness, hence, the floor system in Dhajji-Dewari buildings is expected to behave as a flexible diaphragm. In addition, the roof truss, when placed eccentrically with the timber posts induces torsion. The absence of bracings in the plane of the roof truss induces flexibility and the possibility of relative movements.

(a) Duzce earthquake, 1999 (Langenbach 2020)

(b) Kashmir earthquake, 2005 (Langenbach 2007)

Figure 2.67: Past seismic performance of Dhajji-Dewari buildings

2.4.8 Earthquake-Resilient Features

Dhajji-Dewari buildings possess several earthquake-resilient characteristics in their siting, architectural, and structural features that are shown in Figs. 2.68-2.69. Starting from the site selection, it is usual practice to construct these buildings on flat terrain or artificially created flat terrain. As a result, these buildings are regular in shape in both plan and elevation. The plan dimensions of the Dhajji-Dewari buildings are chosen to result in a rectangular plan shape with a plan aspect ratio not exceeding 3. Dhajji-Dewari buildings have more or less uniform distribution of walls in two directions. The Dhajji-Dewari buildings are timber-heavy construction with the least thickness of walls, hence, these features reduce the overall seismic weight of the Dhajji-Dewari buildings thereby minimizing the overturning effects thus providing overall stability to these buildings.

Dhajji-Dewari buildings offer a complete load transfer path for earthquake forces. The use of weak (mud) mortar (which is the most important attribute of the Dhajji-Dewari buildings) results in in-plane cracking of masonry walls under the action of an earthquake, thereby absorbing seismic energy through friction against the timber framing, and also between the cracks in the infill material. Cracking in walls of Dhajji-Dewari buildings increases their flexibility, as a result, the timber frame remains elastic, maintains its stability, and continues to support gravity loads. The timber frame and closely spaced bracing essentially remain elastic and prevent the formation of large cracks and their propagation through the infill walls and thus protect the walls to fail in the out-of-plane direction. The timber lacing subdivides the vertical span of the masonry in walls which is one of the earthquake-resilient features of Dhajji-Dewari buildings. The uniform alignment of openings in Dhajji-buildings with timber braces does not possess any threat to the walls. The good quality of loose-fit connections between the various structural timber elements in Dhajji buildings further adds to their earthquake resilience. Dhajji-Dewari buildings have approximately one-fourth of the seismic weight as compared to the other traditional timber-laced stone masonry buildings (due to thinner walls 0.110 m in Dhajji buildings against 0.45 m in timber-laced stone masonry buildings) of the same size. Thus, Dhajji-Dewari buildings attract significantly smaller seismic forces as compared to timber-laced stone masonry buildings. When the walls from two perpendicular directions are appropriately connected, the infills can fail during the high intensity of earthquake whereas the timber frame remains intact and remain capable of transmitting gravity loads. In addition, the experimental investigation (Ali et al. 2012) on Dhajji-Dewari walls suggests a high damping ratio (up to 25% at a drift ratio of 5%) in the inelastic range, associated with the infilled timber frame further helps in minimizing the impact of earthquakes on Dhajji-Dewari buildings by reducing the force demands on these buildings. It was further recommended (Ali et al. 2012) to use a ‘Response Reduction Factor’ of 2 for Dhajji-Dewari structures.

2.4.9 Suggested Seismic Safety Measures

Though Dhajji-Dewari buildings have performed well during past earthquakes, they can still be improved in terms of the connections among the structural members. Further, the floors and roofs in Dhajji-Dewari buildings have limited rigidity in their plane. Hence, the measures that can be adopted to improve these features are suggested in Figs. 2.70-2.72. The in-plane rigidity of the floor system of Dhajji-Dewari buildings can be improved either by providing and nailing additional timber planks perpendicular to the existing timber planks, cross-timber planks or by providing carbon fiber reinforced polymer (CFRP) straps using epoxy diagonally (Gattesco and Macorini 2014) as shown in Fig. 2.70. Further, for improving the rigidity of the roof system in Dhajji-Dewari buildings, the timber/metal diagonal bracings can be added and connected to the existing roof. The typical connections used in timber frames between various structural elements can be improved using blocking pads or metal straps (Schacher and Ali 2009) as shown in Fig. 2.70. Similarly, the rafter-to-tie beam and post-to-brace connections can also be improved using metal straps (Fig. 2.72).

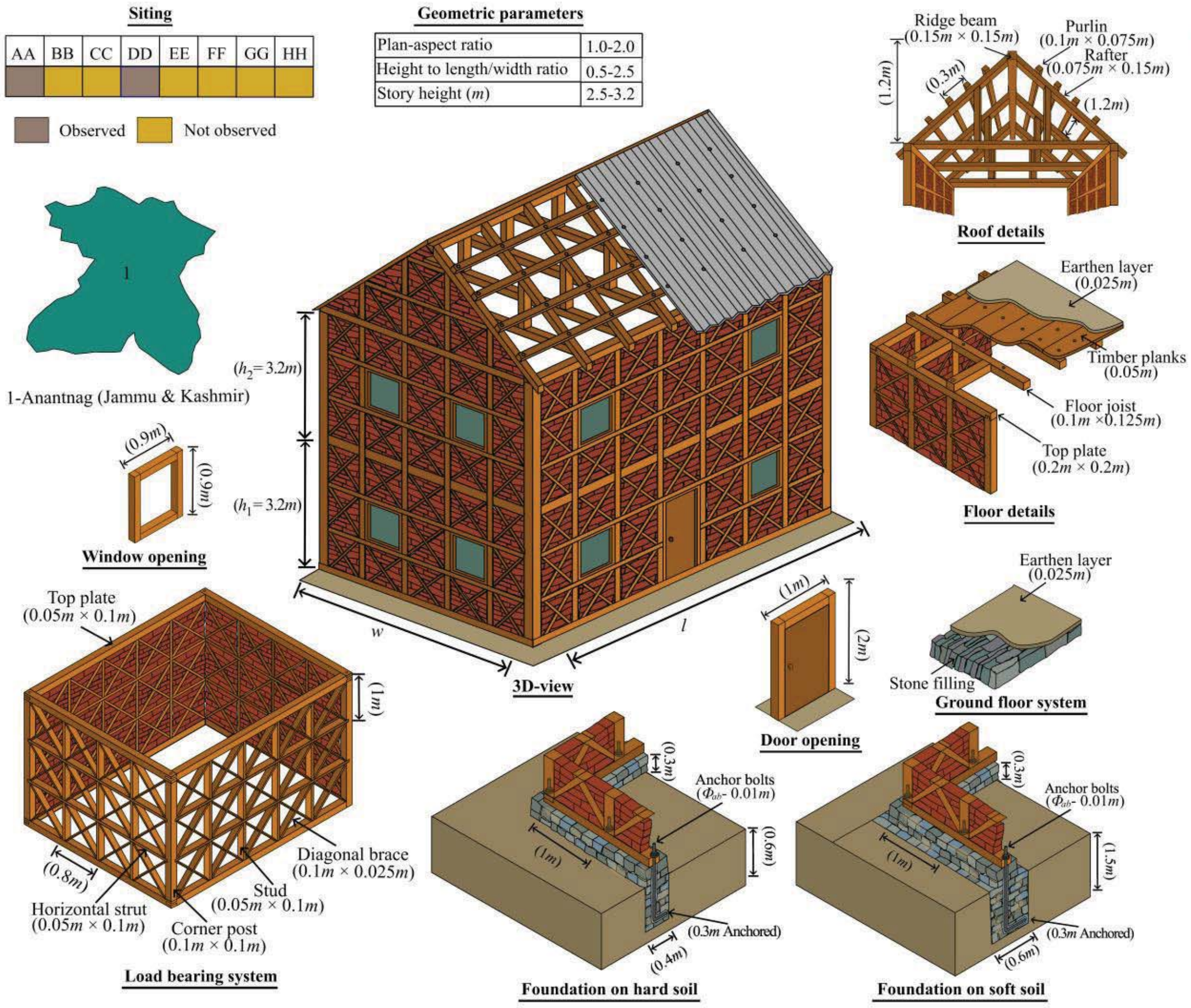
Siting

AA	BB	CC	DD	EE	FF	GG	HH
🟫	🟨	🟨	🟫	🟨	🟨	🟨	🟨

🟫 Observed 🟨 Not observed

Geometric parameters

Plan-aspect ratio	1.0-2.0
Height to length/width ratio	0.5-2.5
Story height (m)	2.5-3.2



h_i= height of i^{th}story, l = length of building, w = width of building , Φ_{ab} = diameter of anchor bolts

Impact of observed features on earthquake-resilience

Features	Sub-Features	Tag
Siting	Flat ground	🟩
Architectural features	Plan	🟨
	Elevation	🟩
	Small horizontal projections	🟩
	Symmetry of wall/frame	🟩
	Placement of openings	🟩
	Number of openings	🟩
	Uniformity of story height	🟩
	Number of stories	🟩
	Gap between buildings	🟨
Structural features	Gravity/lateral load path	🟩
	Redundancy	🟩
	Roof weight	🟩
	Roof-to-wall/frame connection	🟩
	Wall/frame-to-foundation connection	🟩
	Roof connections	🟩
	Floor-to-wall connections	🟩
	Roof rigidity	🟥
	Floor rigidity	🟥
Soil condition and foundation	Soil condition	🟨
	Foundation size	🟩
Visual conditions	Visual condition	🟨
	Maintenance	🟨
	Material deterioration	🟨
Other	Seismic weight	🟩
	Damping	🟩
	Deformability	🟩

🟩 **Earthquake-resilient**

🟥 **Earthquake-vulnerable**

🟨 **Earthquake resilient/vulnerable**

Figure 2.68: Summary of key features in Dhajji-Dewari buildings

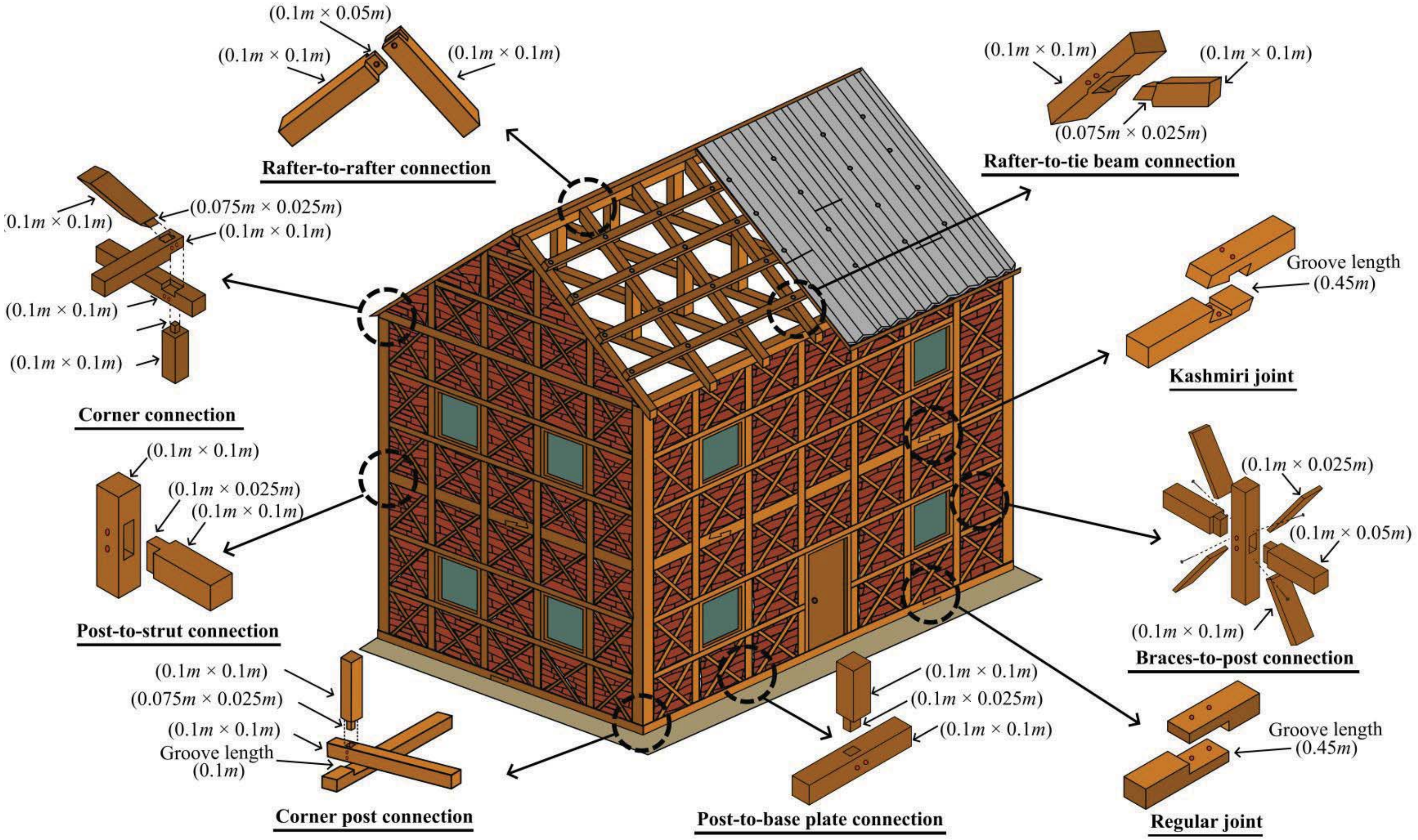
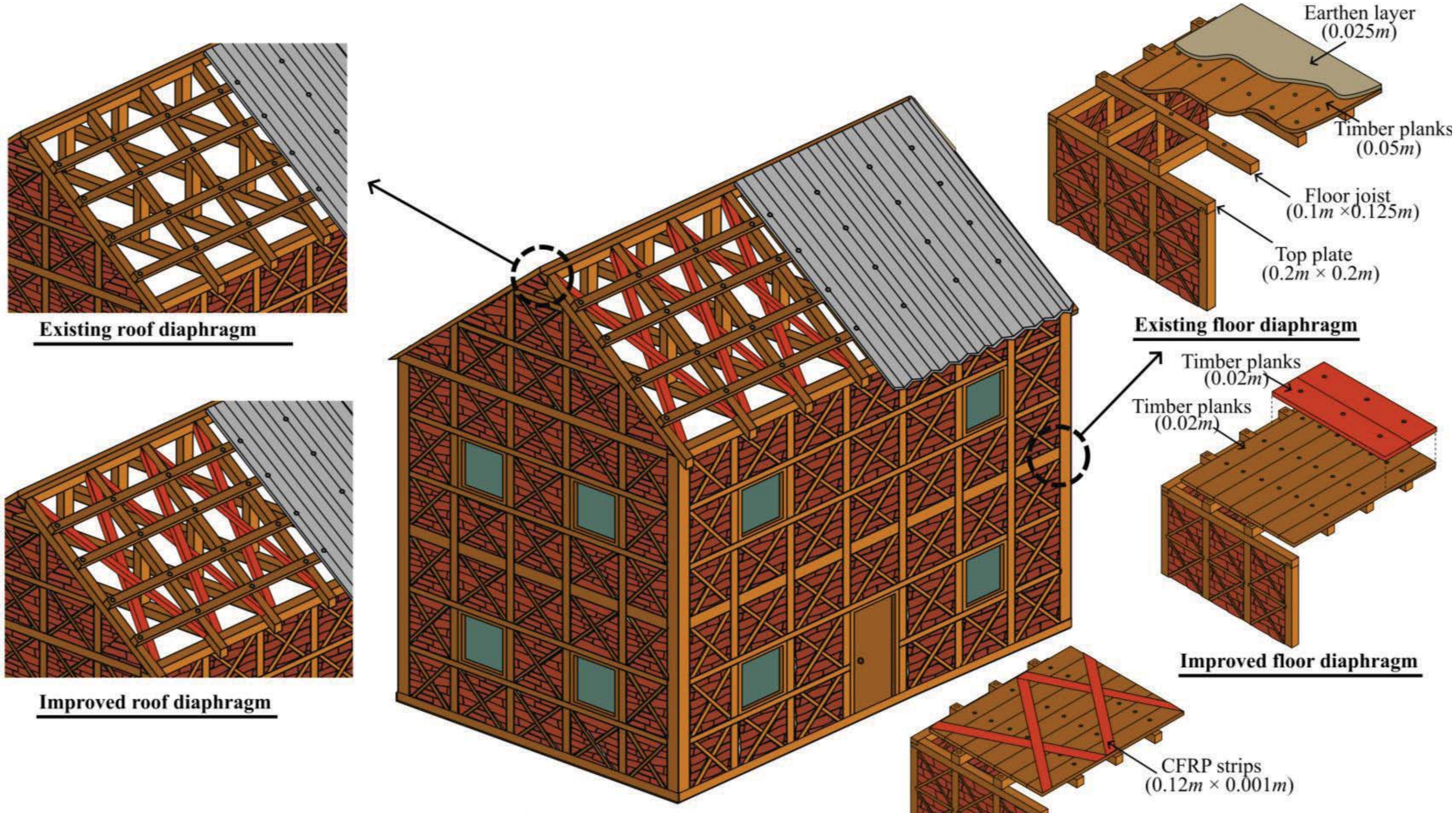


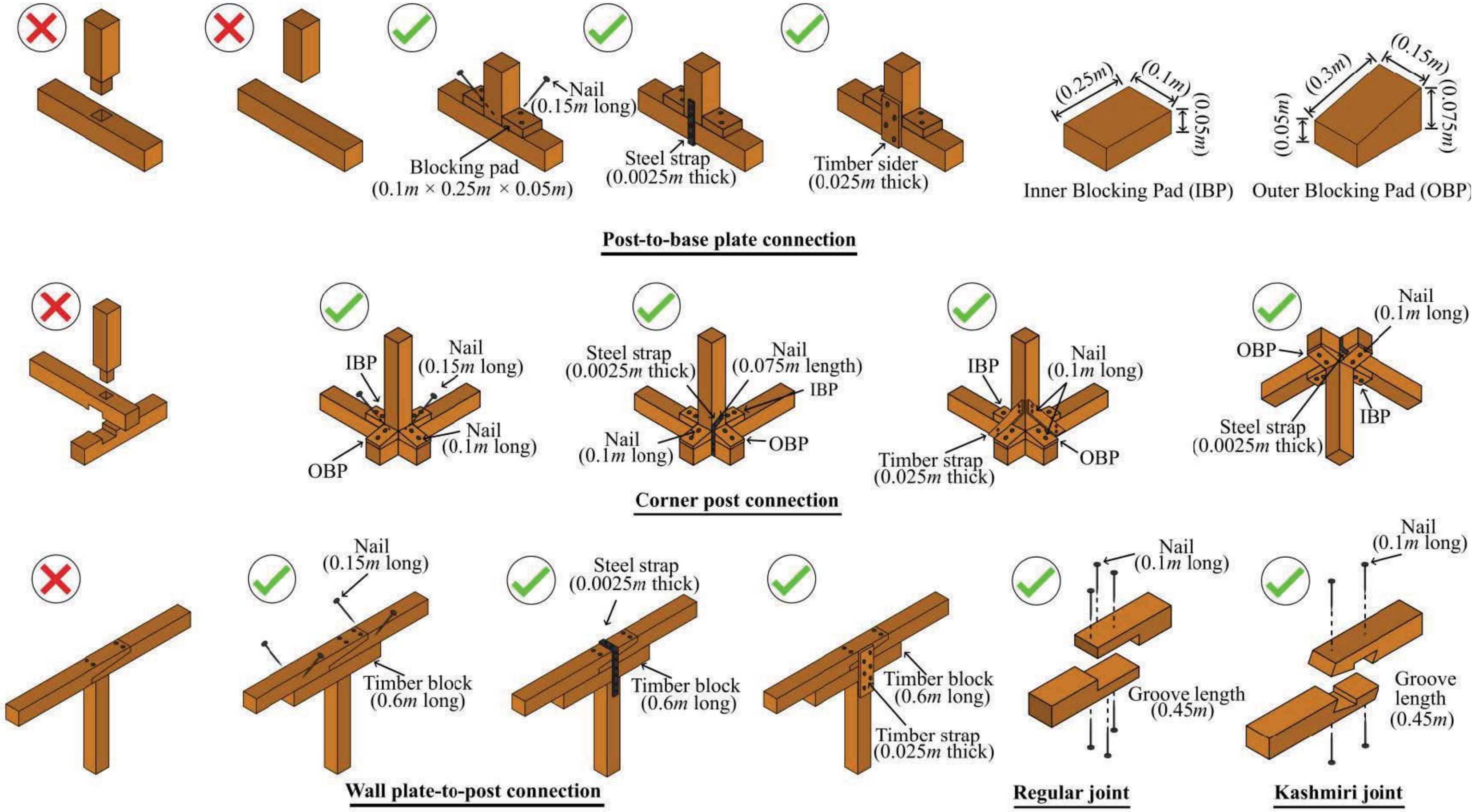
Figure 2.69: Connection details of Dhajji-Dewari buildings



Characteristics of CFRP strips

Fiber Content (%)	65	Laminate Width (mm)	120
Effective Thickness (mm)	1	Maximum Elongation (%)	1.44
Tensile Strength (MPa)	2850	Density (g/cm^3)	1.6
Youngs Modulus (GPa)	175	Application Tempreature (C^o)	-40 to 130

Figure 2.70: Suggested seismic safety measures for Dhajji-Dewari buildings



Note: For wall plate-to-post connection, additional timber block (capital) of minimum 0.1*m* thickness & 0.6*m* length shall be used

Figure 2.71: Suggested strengthening measures for improving timber frame connections in Dhajji-Dewari buildings

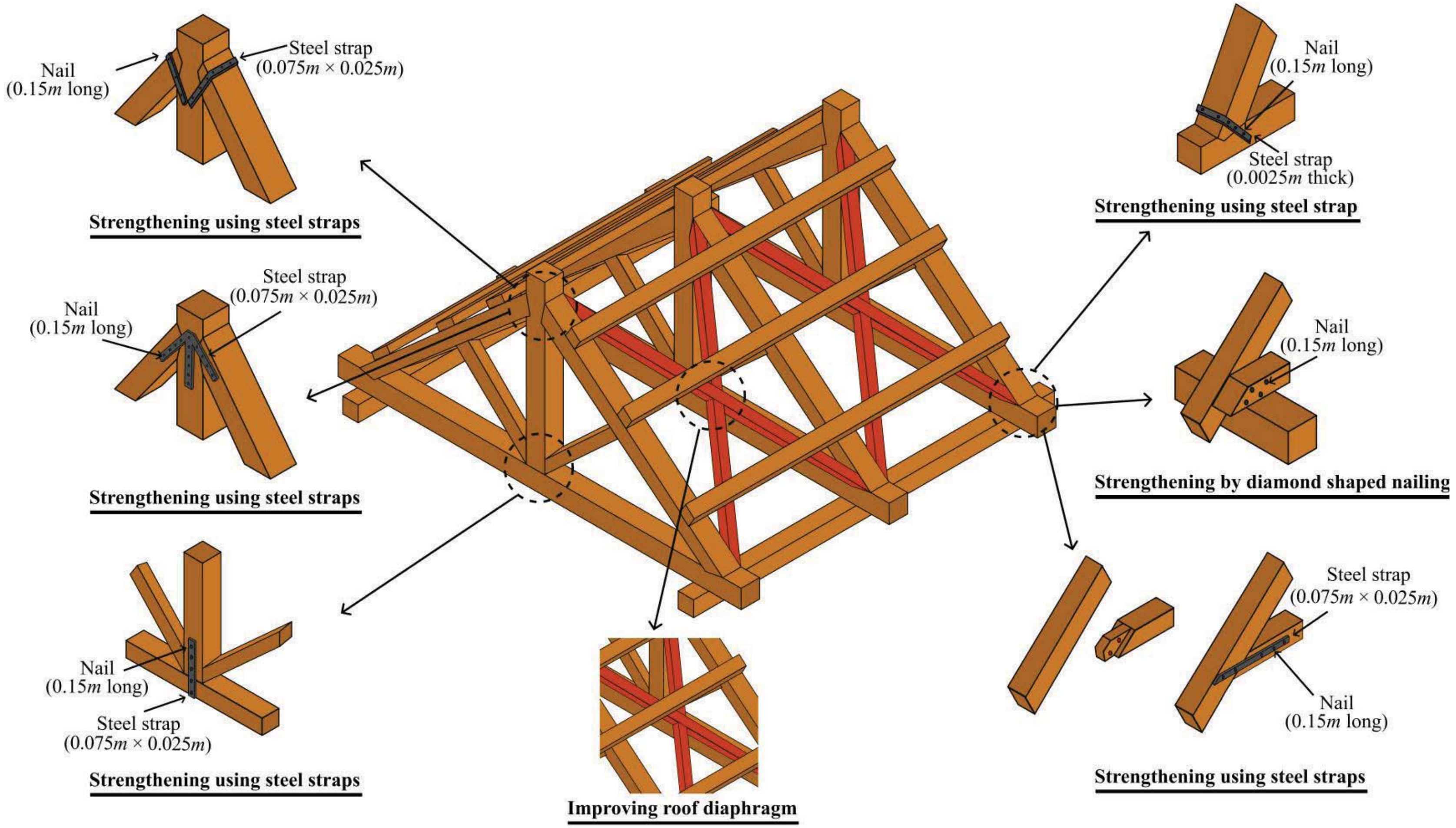


Figure 2.72: Suggested strengthening measures for improving connections of roof system in Dhajji-Dewari buildings

2.5 Taq Buildings

2.5.1 Introduction

Taq is a traditional timber-laced masonry construction practice prevalent in Western Himalayas in Kashmir Valley around Srinagar, in the union territory of Jammu and Kashmir, India (Fig. 2.73). In the literature, this type of construction is also known by the Pashto word "Bhatar" which also describes timber-laced masonry buildings, though; it is specifically used for timber-laced stone masonry buildings. Taq construction practice is a very older construction practice whose mention exists in text from the 12th century (Langenbach 2009). The specific name of this traditional typology 'Taq' actually indicates 'the distance between the piers comprising a bay' in the building. These traditional buildings are considered the choice among the low-to-middle socio-economic groups. Walls in Taq buildings are traditionally made of a mixture of brick and rubble stone or sun-dried bricks laid in thick mud mortar with load-bearing piers at regular intervals. The exterior face of the walls is made of hard-fired bricks whereas the interior face of the walls is made of sun-dried bricks. Deodar or Kail timber is used for the construction of timber lacings/floors and roofs. One of the peculiar features of Taq construction is the bearing wall masonry has horizontal ladder-like timber lacings at multiple locations within a floor. These timber lacings serve to hold the masonry walls together and tie them to the floors. Taq buildings are clustered into smaller regions which are referred to as Mohallas.

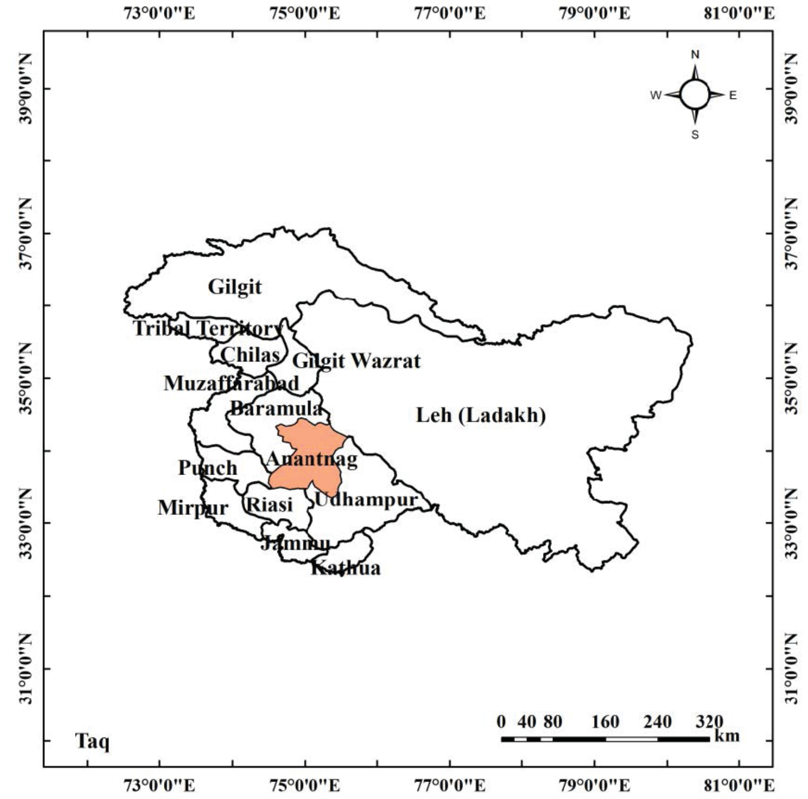


Figure 2.73: Map showing the regions of the prevalence of the Taq buildings

2.5.2 Siting

The siting of a building plays a crucial role in the overall seismic response of the building. Even though the Taq buildings are practiced in a region where topographic features exist, they are seen to be only constructed on flat ground conditions (Fig. 2.74). When sloping ground conditions are encountered, the ground is artificially created plain by constructing a stone masonry platform and a building is constructed above it.

(a) On flat ground (b) On flat ground

Figure 2.74: Different siting of Taq buildings

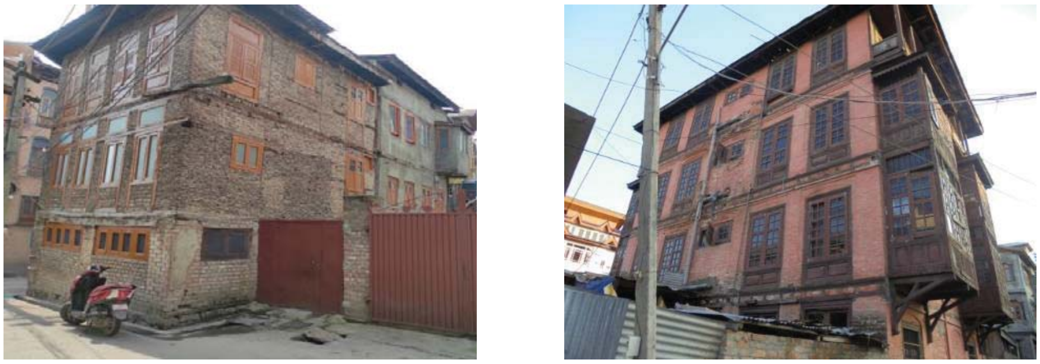
2.5.3 Architectural Features

Taq buildings are not only limited to residential buildings but are also used in the construction of schools, temples, or mosques in the study region. The residential buildings of Taq are generally occupied by joint families and in some parts of the city, shops or even small manufacturing units are functional along with residences that are built in Taq style (Fig. 2.75). The Taq buildings are constructed considering the fundamental principles of earthquake safety. Accordingly, Taq buildings are seen with a square to rectangular plan shape with a few exceptions where complex plan shapes are also seen (Fig. 2.76). The plan aspect ratio for the Taq buildings typically ranges between 1 and 2.5 (Fig. 2.76). Taq buildings are seen with their length varying between 10-20 m and the width varying between 10-12 m (Fig. 2.76).

(a) Residential building (b) Residential-Commercial building

Figure 2.75: Different occupancies in Taq buildings

In general, in Taq buildings, windows are provided on all sides and closed with two sets of shutters: (i) the inside set being of solid wood, and (ii) the outside with jalli, an open filigree of carved wood (Fig. 2.77). To allow light into the house, oiled newspapers were stuck to jalli traditionally. Recently, traditional window provisions in Taq buildings are modified and glass windows are also seen. In Taq buildings, large openings (up to 1.5-2 m wide) are provided that cover up to 70-80% of the wall length (Fig. 2.77). Larger openings are kept in Taq construction to ensure adequate lighting in the room. Above these openings, Taq buildings have provisions of lintels that are not continuous in the walls. The number of stories in Taq buildings can be up to 4 stories (Fig. 2.76). The story height is the Taq buildings vary from 2.8-3.2 m (Fig. 2.75).



(a) Rectangular plan

(b) Rectangular plan

(c) Rectangular plan

(d) Complex plan

Figure 2.76: Plan shapes in Taq buildings

(a) Windows on two sides

(b) Windows with jalli

(c) Openings between Taq piers

(d) Large openings

Figure 2.77: Openings in Taq buildings

(a) Small Horizontal projections (b) Small horizontal projections

(c) Small horizontal projections (d) Large horizontal projections

Figure 2.78: Horizontal projections in Taq buildings

(a) Gap between two buildings (b) Adjacent building

(c) Gap between two buildings (d) Gap between two buildings

Figure 2.79: Gap between adjacent Taq buildings

During the winter season, the topmost floor is used for storage. In most of the Taq buildings, toilets are constructed away from the house (usually in the front court). The living room and kitchen are usually kept on the ground floor and bedrooms are generally situated on the upper floors. Taq buildings have horizontal projections that are called ‘Taqshe’ locally, whose lengths typically vary between 1-1.5 m (Fig. 2.77). Usually, Taq buildings do not share their walls with adjacent buildings. However, many closely spaced buildings were also seen in the study region (Fig. 2.79).

2.5.4 Structural Features

2.5.4.1 Load-bearing Wall System

The load-bearing system of the Taq building is timber-laced masonry (Maharaji or sun-dried bricks at the upper floors and random rubble stones at the lowermost floor) with large timber runners embedded in heavy masonry walls (Fig. 2.80(a)-(d)). The face bricks used during the 19th and early 20th centuries are rough-surfaced, quite small in size, and hard-fired bricks which are called Maharaji bricks (Fig. 2.80(a)). Maharaji bricks are weather-resistant, locally burnt bricks that are half the size of modern bricks. The size of bricks that are currently being used in Taq construction is 0.065 X 0.115 X 0.23 m. Taq building walls are raised on a plinth made of rubble stone, up to a height of 1-1.5 m (Fig. 2.80(b)). The horizontal runners (bands) are placed on masonry walls without any connections. The walls are laid using a combination of rubble stones and bricks laid on thick mud mortar. There are two different levels of timber band used at each story level that are namely - ceiling band and floor band. The ceiling band represents the end of the lower story whereas the floor band represents the beginning level of the upper story.

(a) Timber runners at story levels

(b) Raised plinth

(c) Timber runners with cross-piece

(d) Discontinuous window lintel

Figure 2.80: Structural features of Taq buildings

The two parallel timber runners are connected with a cross-piece, usually at the bottom of the runners (Fig. 2.80(c)). The timbers runners are further lapped at the cross wall (Figs. 2.80 and 2.81). In a few buildings, the timber runners are also seen just above the window, however, they were not continuous (Fig. 2.80). One of the interesting features of the Taq construction is that the wall openings lie between two piers (Fig. 2.82(a) and (b)) and the piers and wall opening surroundings have unbonded butt joints without any mortar (Fig. 2.82(d)). The piers in Taq construction are usually of square to rectangular shapes with their cross-section typically between 0.75 x 0.75 m to 0.9 x 0.9 m (Fig. 2.82(c)). The distance between two Taq (piers) is typically between 1.4-1.8 m (Fig. 2.82(c).

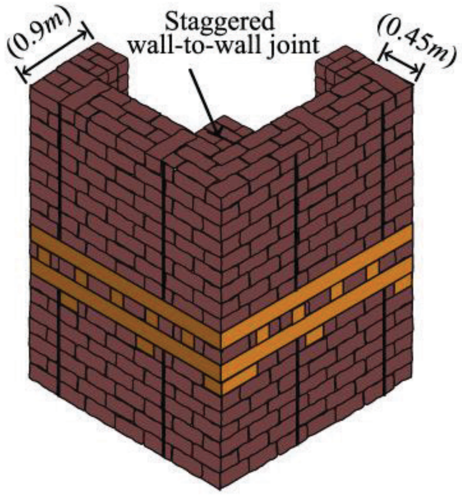


Figure 2.81: Typical sketch of the load-bearing system in Taq buildings

(a) A building with five Taq piers

(b) Taq pier

(c) Internal view of Taq piers

(d) Unbonded butt joint

Figure 2.82: Taq piers and their details

Traditionally, the internal walls are thinner walls made of wattle and daub (thin walls made of wooden strips and sticky paste) or thin timber walls with thicknesses ranging between 0.1-0.15 m. The walls of Taq buildings are generally not plastered externally. However, the internal walls are plastered using a mixture of clay and straw that offer adequate insulation. A mixture of clay and water is applied to the existing surface to renew the plastered walls. Apart from providing thermal insulation, mud mortar also assists in keeping the masonry walls together during an earthquake by imparting some amount of compressive strength. In many cases, Taq buildings are seen with a combination of timber frames (Dhajji-Dewari) in the uppermost stories to reduce the seismic weight of these buildings (Fig. 2.83).

(a) Dhajji-dewari at upper stories (b) Dhajji-dewari at upper stories

Figure 2.83: Intermixing of Taq and Dhajji-dewari structural systems

2.5.4.2 Floor Systems

The ground floor of the Taq building usually consists of stone filling overlaid with mud flooring. The upper floor system in Taq construction practice is generally made of wooden joists on which wooden planks rest that are covered with mud as shown in Fig.2.84. At the floor level, the timber floor joists (of sizing 0.10 m x 0.15 m) comprise two sets of ladder-like timber bracings. Hence, the wooden beams tie the floors of the structure together with the walls. Timber beams locally called ‘Ker’ sandwich the floor joists between them (floor joists between double bands) and at the ends, the floor joists protrude out of the walls. There are 3 levels of timber band (Fig. 2.85) used in each story level that is namely - ceiling band, floor band, and floor joists (no particular connection observed), and the timber planks are nailed to floor joists that are spaced around 0.4 m. The floor joists rest on piers which enables complete load transfer from floor to piers. Cross-planks or any other arrangements are not seen in the floor system thus the floor system is expected to behave as a flexible diaphragm.

2.5.4.3 Roof Geometry and Systems

The timber members used in the roof trusses are quite heavy and not sawn, hence it is difficult to make proper connections between the elements. Furthermore, these heavy timber members contribute to the mass which is needed to hold down the floor band. In modern times, the traditional bark roofing (not observed during field surveys) is replaced with CGI sheets as shown in Fig. 2.86. Traditionally in the roof system, barks were provided for roofing that was covered by mud. The occupants responded that during summer, roofs are covered with grasses and tulips. However, such roof systems weren’t observed during the survey. The roof system primarily rests on piers and hence a complete load transfer system from the roof to the wall is well established. During construction, wall piers, and roof system is constructed first followed by the completion of the rest of the walls.

The roof system of Taq buildings is mostly of gable roofs comprising ridge beams, tie beams, lateral boards, braces, king & queen posts, rafters & purlins. Heavy large sections of tie beams are placed on wall plates without any connection. Rafters are connected to ridge beams (also referred to as nar kooth that run throughout the length of the building) with grooves and nailing. King & queen posts are connected to the rafter and tie beam with the help of tenon and mortise joints. No cross-bracings were observed in the roof truss. A typical sketch of the roof system of Taq buildings is shown in Fig. 2.87.

(a) Mud floor (b) Floor system

(a) Floor system (b) Floor system

(c) Floor system (d) Floor system

Figure 2.84: Floor systems in Taq buildings

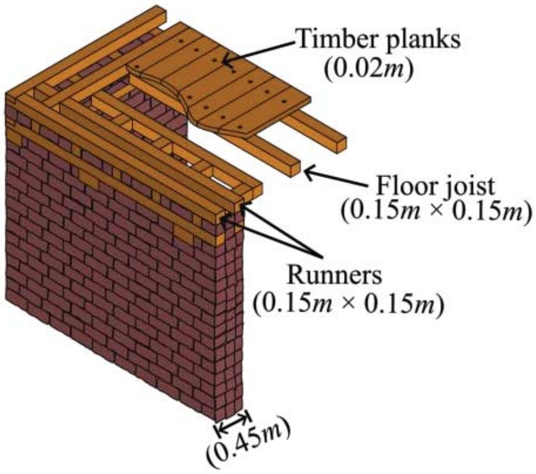


Figure 2.85: Typical sketch of the floor systems in Taq buildings

(a) Gable roof with CGI sheets

(b) Gable roof with CGI sheets

(c) Roof system

(d) Braces and queen posts

Figure 2.86: Roof systems in Taq buildings

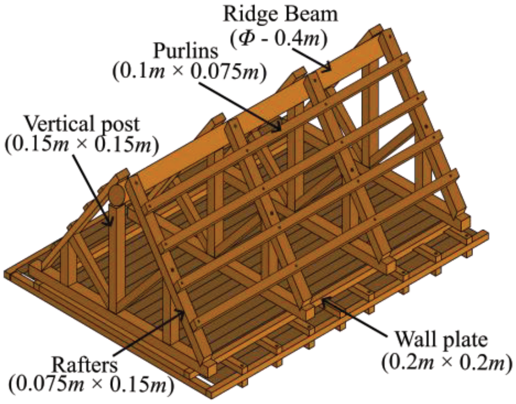


Figure 2.87: Typical sketch of the roof systems in Taq buildings

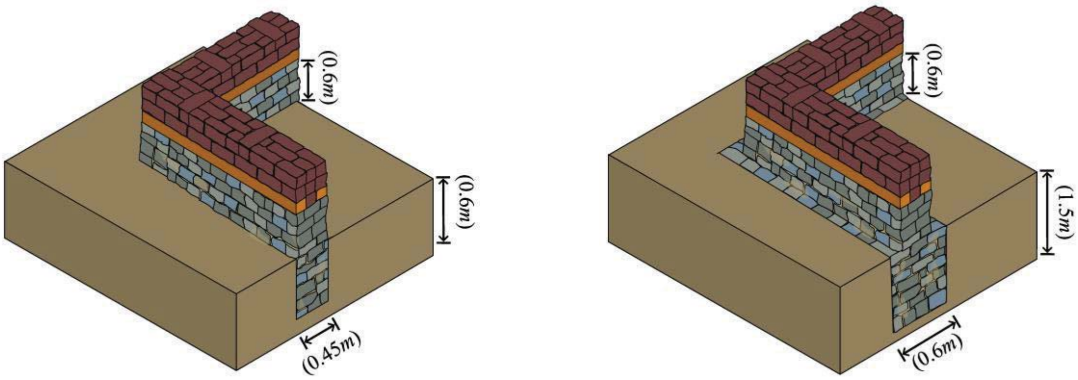
2.5.4.4 Soil Conditions and Foundations

Taq buildings rest on shallow foundations made of rubble stone on which a plinth level of 0.3-1 m is raised using the rubble stones (Fig. 2.88). Above the foundation, there are timber bands called dassa that serve as plinth bands. The depth and width of the foundation vary according to the local soil characteristics (Fig. 2.89). The majority of the soil in the area where Taq construction is common is soft, and when compared to other traditional Himalayan methods, the width and depth of the foundation in Taq construction are considerably larger. The typical sketch of the foundation of Taq buildings is shown in Fig. 2.89.

(a) Stone foundation (b) Stone foundation

(c) Plinth band on the stone foundation (d) Stone foundation

Figure 2.88: Foundations in Taq buildings



(a) Foundation on hard soil (b) Foundation on hard soil

Figure 2.89: Typical sketches of foundations in Taq buildings

2.5.5 Visual Conditions and Maintenance

The visual conditions of the Taq buildings when surveyed were found to be average to good. As exterior walls are not plastered, the timber bands are subjected to degradation due to direct exposure to the external environment. Fig. 2.90 shows cracks in walls observed during survey.

(a) Crack in walls (b) Crack in walls

Figure 2.90: Visual conditions of Taq buildings

2.5.6 Contemporary Modifications

Contemporary modifications exist in Taq buildings however such modifications are mostly incompatible. The contemporary practices include the use of cement plaster on walls, and use of the modern bricks against traditional Maharaji bricks (Fig. 2.91). The manufacture of Maharaji bricks has also become nil leading to the use of modern bricks in Taq buildings. Due to the unavailability of wood and the decline in the quality of craftsmanship over time, CGI sheets are used as roofing material instead of traditional sod roofs (bark roof).

(a) Cement plaster (b) Cement plaster

(c) Modern bricks (d) Modern bricks & CGI sheets

Figure 2.91: Influence of contemporary materials in Taq buildings

2.5.7 Past Seismic Performance and Vulnerability

The investigations conducted in this study suggest the origin of the Taq construction at least 10 centuries before the present time. However, the exact age of these buildings is unknown. The Himalayan region where Taq buildings are prevalent faced several multiple strong earthquakes in the past few centuries, however, limited literature exists that talks about the seismic performance of Taq buildings under past earthquakes. During the 1967 Kashmir earthquake (Mw=5.5), Taq buildings up to 3-story survived without any damage, due to the use of large volumes of timber (Gosain and Arya 1967). More recently, it was the 2005 Kashmir earthquake (Mw=7.6), that showed its excellent seismic performance, even though the region suffered extensive damage to the other building types. When asked about the performance of the Taq buildings the occupants recollected that during the Kashmir earthquake, Taq buildings performed very well with only little damage. After the 2005 Kashmir earthquake, Langenbach (2005) reported that timber lacing in masonry building construction has proven to substantially reduce the likelihood of collapse and leaves buildings in a restorable condition that can also, in many instances, be safely occupied in a damaged state. Similarly, Rai and Murthy (2006) reported no to very little damage to timber-laced buildings as compared to masonry buildings during the 2005 Kashmir earthquake. No collapse has been observed for such timber-laced masonry even in the areas of higher shaking.

The few specific features that could add to the seismic vulnerability of Taq buildings include too large horizontal projections. In addition, these buildings are closely spaced which could lead to pounding failure as observed during the 2005 Kashmir earthquake (Langenbach 2005). Further, the timber planks are nailed to floor joists, thus, they offer very limited in-plane stiffness, hence, the floor system in Taq buildings is expected to behave as a flexible diaphragm. The absence of bracings in the plane of the roof truss induces flexibility and the possibility of relative movements.

2.5.8 Earthquake-Resilient Features

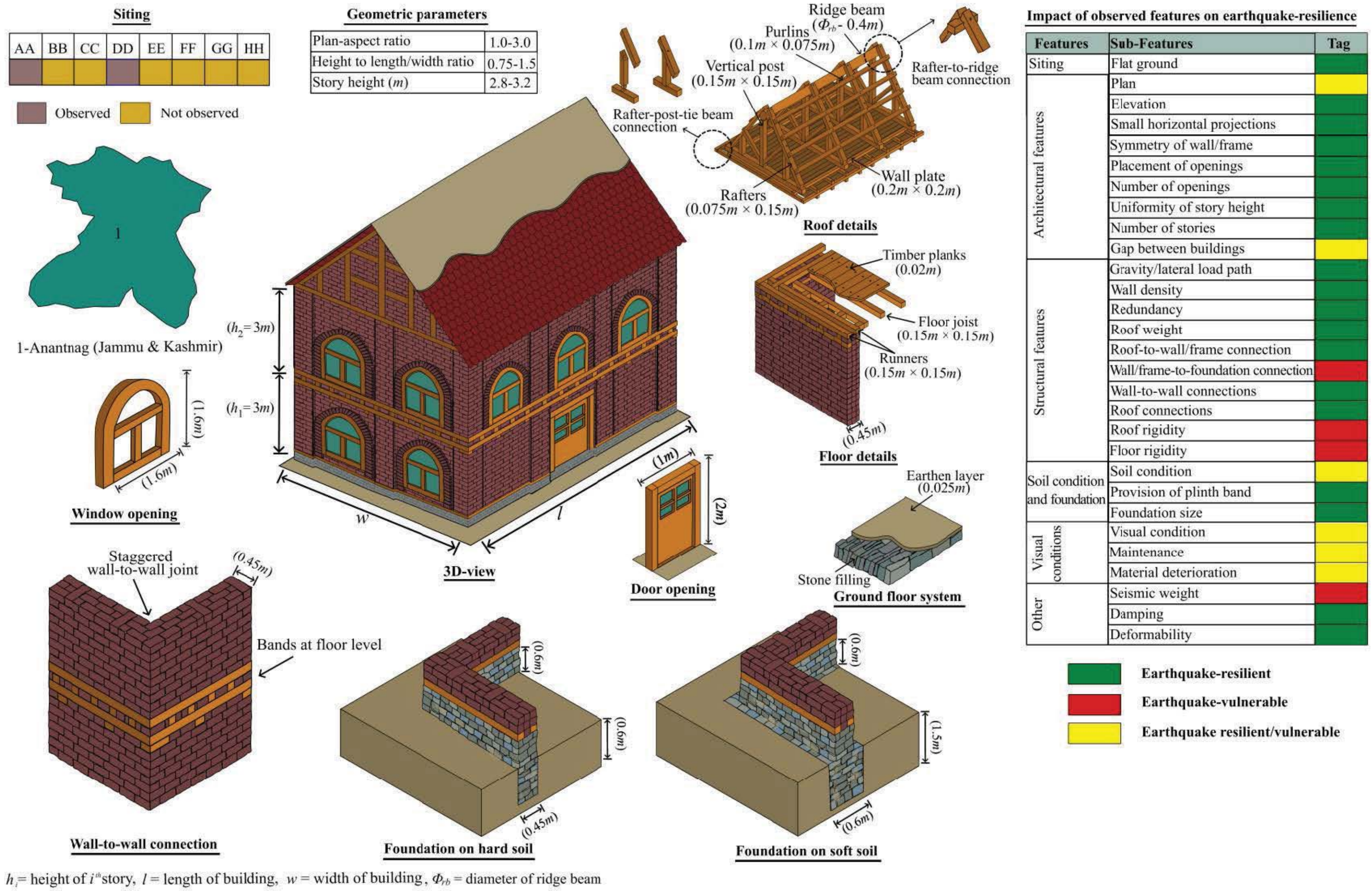
Taq buildings possess several earthquake-resilient characteristics in their siting, architectural, and structural features that are summarized in Fig. 2.91. Starting from the site selection, it is usual practice to construct these buildings on flat terrain. As a result, these buildings are regular in shape in both plan and elevation. The plan dimensions of the Taq buildings are chosen to result in a rectangular plan shape. The seismic weight of the floors in Taq buildings gradually reduces from the bottom to the top (the bottom stories usually have stone masonry walls and the topmost story has the Dhajji-system). As a result, the center of gravity of these buildings is closer to the ground and which overall adds to their stability against overturning. Though the Taq buildings are characterized by the large openings in their walls, these openings do not affect their seismic resistance significantly, as the Taq buildings derive their earthquake resistance from the heavy masonry piers in between the openings.

The timber bands and heavy masonry piers form the structural system of Taq buildings. The timber lacings are continuous and are provided on all four sides of the walls. The timber bands in Taq buildings are well-jointed that offer a connection between the cross-walls and tie walls, and also prevent the separation of piers during an earthquake. Heavy timber on masonry walls holds the masonry walls together as they are sandwiched between timber bands. Both floor and roof systems rest on top of thick piers (height-to-thickness ratio up to 4.5) laid in the thick mortar that offers a complete load transfer path from the roof to the foundation. The thick piers are unbonded to masonry walls thus crack propagation can be avoided and due to the heaviness of masonry, the structure is prestressed against lateral forces. Friction induced in masonry units during an earthquake dissipates energy in buildings. The usage of weak mud mortar further enhances the frictional resistance after the cracking of the mortar. The use of weak mud mortar, lack of bond between Taq piers and masonry walls, and the use of a heavy-weight roof system impart both stability and flexibility to the structure in protecting the structures against earthquakes. The gable walls in Taq buildings have a timber frame identical to the Dhajji-dewari system, the failure of the gable end is also prevented in these buildings. Taq buildings have to be regarded as composite building systems in which all the parts are interdependent and work together in a kind of organic balance. Although some of the individual structural elements are brittle, the specific configuration of Taq buildings confers to the system's certain ductility. The friction within the various part of the building system as they are not tightly bound together allows the dissipation of a good amount of the energy induced by an earthquake, preventing the walls from falling apart. One particularity of Taq walls is that the infill masonry panels are not bounded to the piers and a complete load transfer path is established due to heavy piers that are well connected to floor and roof levels. This would allow the building to better adapt to differential settlements, which are frequent on the soft soil of Srinagar.

Apart from these siting, architectural, and structural features, Taq buildings possess other important engineering characteristics related to their construction materials that are very beneficial for their enhanced earthquake resistance. The timber bands along with masonry provide the deformability to the Taq buildings, and thus, increased energy dissipation capacity, and (ii) the timber and bricks in walls of Taq buildings possess a high damping ratio (which could be up to 10% of the critical damping in the undamaged state) as compared to contemporary materials (e.g., reinforced-concrete, where it is 5% of the critical damping in the undamaged state). The increased damping ratio results reduction in the seismic force demands on Taq buildings.

2.5.9 Suggested Seismic Safety Measures

Though Taq buildings have performed well during past earthquakes, they can still be improved in terms of their structural features. The floors and roofs in Taq buildings have limited rigidity in their plane. Hence, the measures that can be adopted to improve these features are suggested in Figs. 2.93. The in-plane rigidity of the floor system of Taq buildings can be improved either by providing and nailing additional timber planks perpendicular to the existing timber planks, cross-timber planks or by providing carbon fibre reinforced polymer (CFRP) straps using epoxy diagonally (Gattesco and Macorini 2014) as shown in Fig. 2.93. Further, for improving the rigidity of the roof system in Taq buildings, the timber/metal diagonal bracings can be added and connected to the existing roof.



Siting

AA	BB	CC	DD	EE	FF	GG	HH
🟪	🟨	🟨	🟪	🟨	🟨	🟨	🟨

🟪 Observed 🟨 Not observed

Geometric parameters

Plan-aspect ratio	1.0-3.0
Height to length/width ratio	0.75-1.5
Story height (*m*)	2.8-3.2

Impact of observed features on earthquake-resilience

Features	Sub-Features	Tag
Siting	Flat ground	🟩
Architectural features	Plan	🟨
	Elevation	🟩
	Small horizontal projections	🟩
	Symmetry of wall/frame	🟩
	Placement of openings	🟩
	Number of openings	🟩
	Uniformity of story height	🟩
	Number of stories	🟩
	Gap between buildings	🟨
Structural features	Gravity/lateral load path	🟩
	Wall density	🟩
	Redundancy	🟩
	Roof weight	🟩
	Roof-to-wall/frame connection	🟩
	Wall/frame-to-foundation connection	🟥
	Wall-to-wall connections	🟩
	Roof connections	🟩
	Roof rigidity	🟥
	Floor rigidity	🟥
Soil condition and foundation	Soil condition	🟨
	Provision of plinth band	🟩
	Foundation size	🟩
Visual conditions	Visual condition	🟨
	Maintenance	🟨
	Material deterioration	🟨
Other	Seismic weight	🟥
	Damping	🟩
	Deformability	🟩

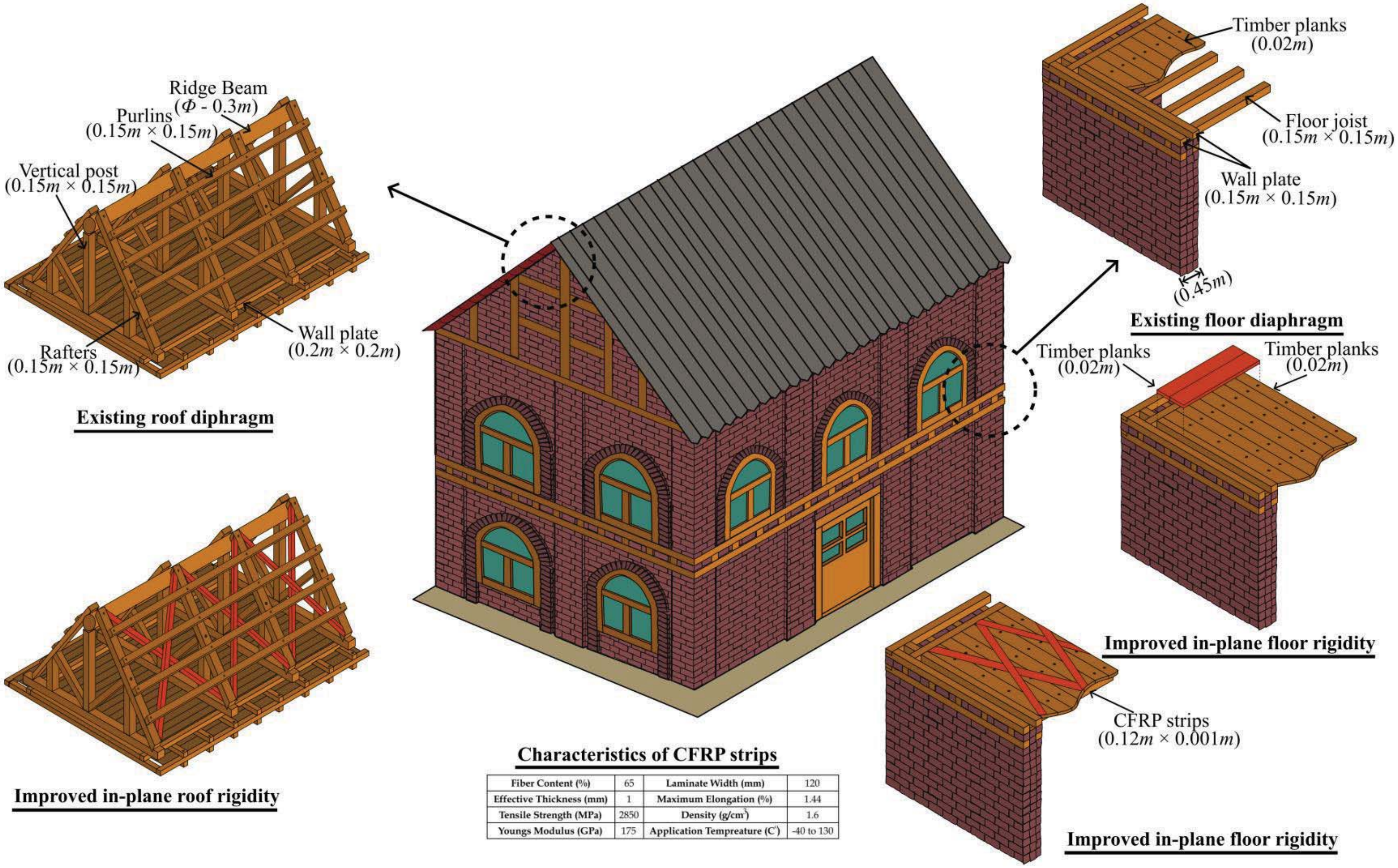
🟩 **Earthquake-resilient**

🟥 **Earthquake-vulnerable**

🟨 **Earthquake resilient/vulnerable**

h_i= height of i^{th} story, l = length of building, w = width of building, Φ_{rb} = diameter of ridge beam

Figure 2.92: Summary of key features in Taq buildings



Characteristics of CFRP strips

Fiber Content (%)	65	Laminate Width (mm)	120
Effective Thickness (mm)	1	Maximum Elongation (%)	1.44
Tensile Strength (MPa)	2850	Density (g/cm^3)	1.6
Youngs Modulus (GPa)	175	Application Tempreature (C°)	-40 to 130

Figure 2.93: Suggested seismic safety measures for Taq buildings

2.6 Assam-Type Buildings

2.6.1 Introduction

Assam-type of building construction is one of the oldest forms of traditional construction widely seen in the Northeastern states of Assam, Sikkim, and Meghalaya (Fig. 2.94). The other regions with the prevalence of this typology are south and southeast Asian countries. The majority of these types of houses are used for residential purposes, and the construction knowledge gained is usually passed on from one generation of local masons to another. However, during British rule, several improvements in the construction practices of Assam-type buildings were implemented. The advantage of these eco-friendly, lightweight buildings was well understood before and after independence and hence several government offices and residences across the states in north-east India were constructed as Assam-type buildings. In many rural areas, typically these houses (referred to as 'Thatch House') are built with locally available lightweight materials such as bamboo, timber, thatch, etc. Even though this building typology is more prevalent in rural areas, a significant percentage of this type of housing can also be found in the cities of the region and also in Guwahati city. However, in the last two decades, a decrease in the number of these traditional houses has been observed, especially in urban areas.

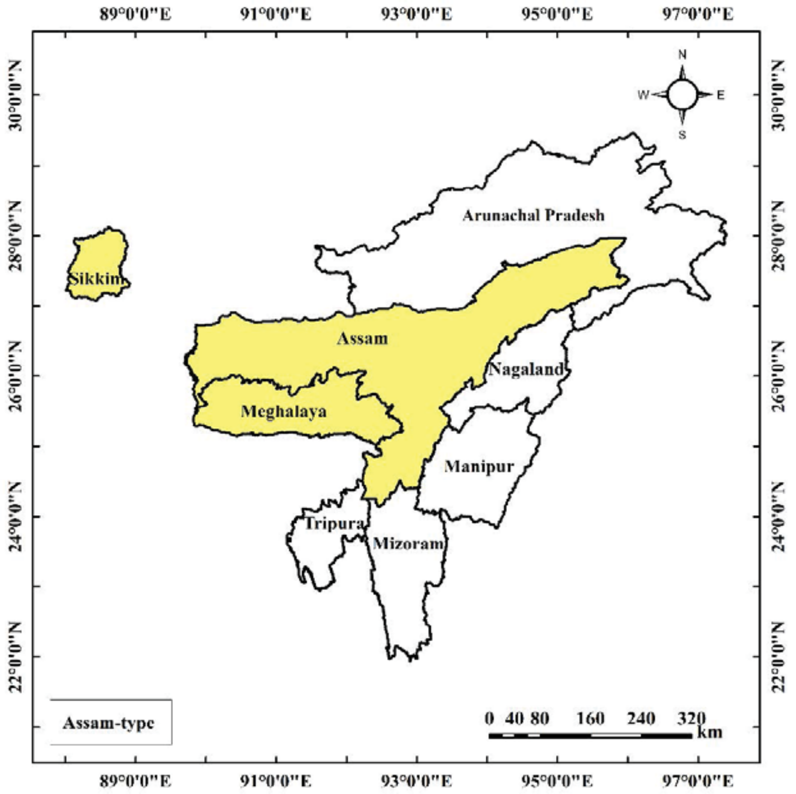


Figure 2.94: Map showing the regions of the prevalence of the Assam-type buildings

2.6.2 Siting

The siting of a building plays a crucial role in achieving adequate seismic performance. Assam-type buildings found in the study region mostly rest on the ground that is characterized by flat topography (Fig.2.95 (a)-(d)). The region where the Assam-type houses are found in prevalence undergoes frequent flooding during the monsoon season. As a result, the other common configuration that can be seen in the Assam-type housing includes the buildings that are supported on the stilts (Fig.2.95 ((e)-(f)). The height of the stilts in Assam-type buildings can be 0.5-1.5 m. When sloped terrain is encountered, the cutting and filling technique is often employed to achieve flat terrain-like conditions and the buildings are constructed over it.

(a) On flat ground (b) On flat ground

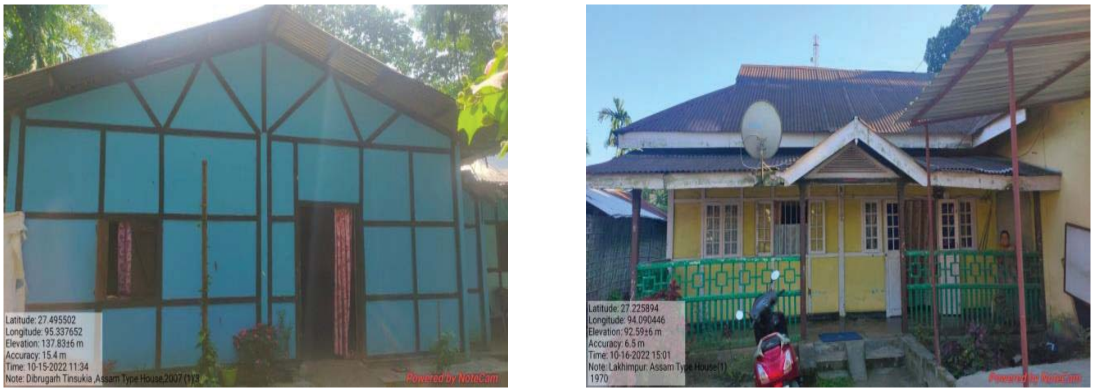
(c) On flat ground (d) On flat ground

(e) On stilts (f) On stilts

Figure 2.95: Siting of Assam-type buildings

2.6.3 Architectural Features

Assam-type houses are seen in a variety of occupancies. These houses are used for residential, commercial, and institutional (government) buildings as shown in Fig. 2.96. In general, Assam-type buildings are constructed following the principles of earthquake safety by maintaining symmetry and regularity in their plan and elevation. It has been observed that Assam-type buildings are constructed with a rectangular plan shape (Fig.2.97 (a) and (b)), with their plan aspect ratios typically varying between 1-2. However, a few exceptions have also been seen during the field surveys, where these buildings are complex plan shapes such as 'L' or 'T' shape plan (Fig.2.97 (c)-(d)).



(a) Residential building (b) Residential building

(c) Residential building (d) Residential building

(e) Office building (f) Office building

Figure 2.96: Occupancies in Assam-type buildings

The Assam-type buildings are low-rise buildings mostly observed to be single-storied, though exceptions are also seen where these buildings are seen as a single story with an attic space or as two-storied buildings (Fig. 2.98). The story height in the Assam-type building typically varies between 2.8-3.5 m, with a raised stone/brick masonry platform of height varying between 0.6-1 m. The Assam-type buildings encompass moderate to large door and window openings between the timber framing. The typical length of openings can vary from 20-60% of the wall length in any given direction (Fig. 2.99). These openings are mostly placed away from the edges and toward the center of the frame. The length and width of Assam-type buildings range between 6-12 m and 6-12 m respectively.

(a) Rectangular plan shape (b) Rectangular plan shape

(c) L-plan shape (d) L-plan shape

Figure 2.97: Plan shapes in Assam-type buildings

(a) Single-story building (b) Single-story building

(c) Single-story with attic space (d) Single-story with attic space

Figure 2.98: Number of stories in Assam-type building

(a) Small openings (b) Closely spaced openings

(c) Uniformly distributed large openings (d) Large openings

Figure 2.99: Openings in Assam-type buildings

Further, Assam-type buildings with residential occupancy have the provision of an open space (verandah) of 2-3 m between the kitchen and the rest of the house to prevent fire accidents. In general, Assam-type buildings are seen without the presence of any horizontal projections except those that are required for roofing. Further, Assam-type buildings are constructed in isolation with gaps as large as tens of meters.

2.6.4 Structural Features

2.6.4.1 Load-bearing Wall-Frame Systems

The traditional Assam-type houses are consisting of walls that are made up of stone/brick masonry up to a height of approximately 0.6-1 m. This brick or stone masonry supports the bamboo/Ikra wall panels that are woven together along with a timber frame. The walls in Assam-type houses are made of ikra (reed) and bamboo of diameters 0.0015 m and 0.025 m, respectively, that are plastered internally and externally using a mixture of mud and cow dung traditionally. The cow dung slurry is also used to fill up the gap between ikra reeds. The walls are further painted on both faces and plaster is re-applied to the walls in cycles. In a few buildings, plastered walls are constructed only up to the lintel level, and above the lintel level, un-plastered walls are constructed that continue up to the roof level. The typical wall density of an Assam-type building can vary between 10-15%. The walls of Assam-type buildings are divided into several smaller panels (Figs. 2.100-2.101). The timber frame of the Assam-type house consists of (i) vertical posts (ii) horizontal struts (iii) corner posts (iv) top plate and (v) bottom plate. The most important part of Assam-type buildings is the connections that exist between various elements. The elements are nailed and bolted formally, but at times are tied together using coir ropes. The vertical intermediate posts are connected to the horizontal struts using steel clamps, bolts, and nails at the floor, sill, lintel, and roof level. The corner posts (0.15 m × 0.15 m) are connected through a combination of grooving and tenon and mortise joints that are nailed as shown in Fig. 2.102. The intermediate vertical elements (0.12 m × 0.12 m) spaced at 1-2 m are connected to horizontal struts through grooves and nails. The main vertical posts are spaced between 2-3 m. The horizontal struts of dimension 0.075 m × 0.075 m are spaced between 0.5-1.5 m and the dimension of the top plate is typically found to be 0.1 m × 0.1 m.

(a) Wall panels and reeds (b) Wall panels

(c) Wall panels (d) Wall panels

Figure 2.100: Wall system in Assam-type buildings

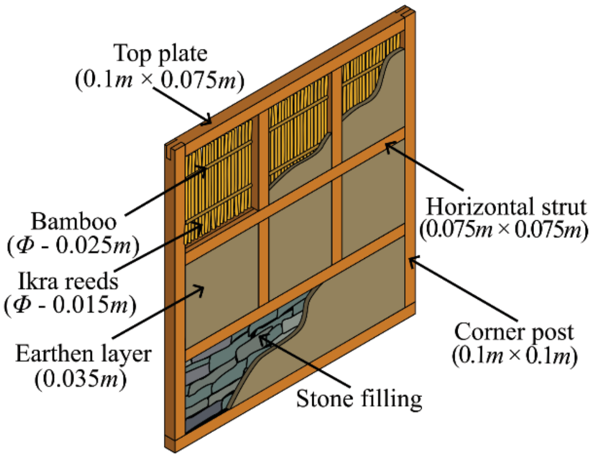


Figure 2.101: Typical sketch of a wall system in Assam-type buildings

Two types of ikra walls are generally constructed namely simple and fine types. In the case of simple ikra walls, ikra is placed vertically outside horizontal battens (bamboo) of the walls and Kami lining (strips made of bamboo, usually 0.015-0.04 m wide) are nailed to the battens at a spacing of 0.3 m. Binding wires are used to tie the kami to the ikra for extra stability at a spacing of 0.3 m. The strengthening of ikra is done by providing one-tier and two-tier kami in an alternative manner vertically at every 0.3 m in between the battens. In the case of fine-type of walls, grooves are made in battens and reeds are slipped through the grooves, and kamis are fitted into the recess in battens. Kamis are tied to battens using binding wires. The horizontal struts are provided at the sill, lintel, floor, and eaves level. A representation of members of the wall system is shown in Fig. 2.101 and the exiting connections in the wall frame system of Assam-type buildings are shown in Fig. 2.102.

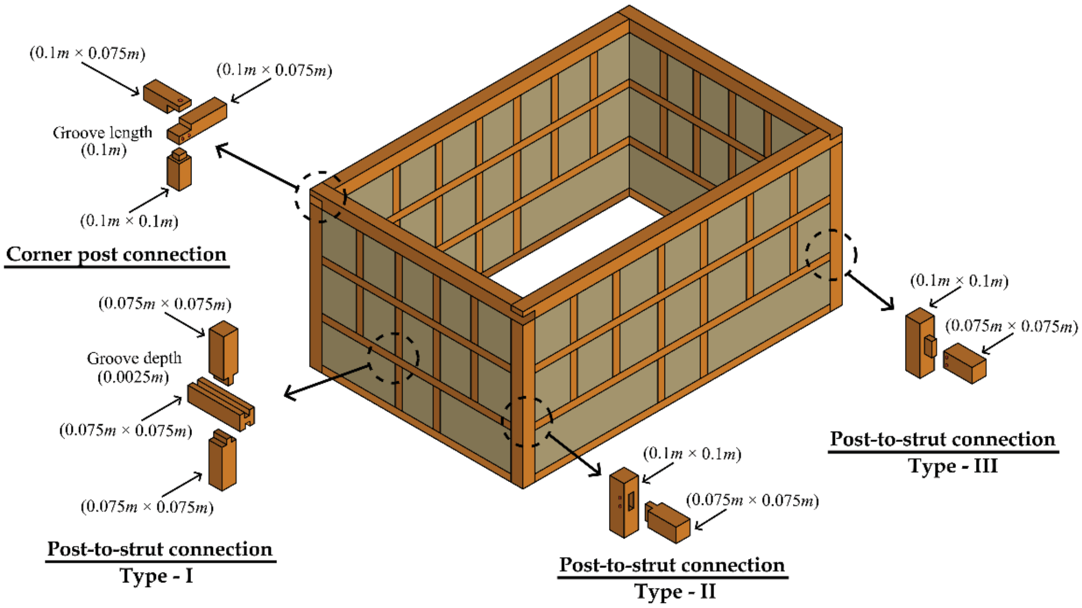


Figure 2.102: Typical sketch of timber framing and its connections in Assam-type buildings

2.6.4.2 Floor Systems

Various floor systems have been observed in Assam-type buildings. In the case of buildings resting on stilts, woven wooden flooring is found. In the case of a 2-story building, the upper floor system consists of floor joists of size 0.05 x 0.1 m that are spaced at 0.3 m and span between primary beams of size 0.12 x 0.12 m that are spaced at 0.6 m. Wooden planks of size 0.025 m are nailed to floor joists. In a few buildings, flooring is done by layering brick or sand followed by cement overlay. The typical span of the floor system is 3 m. Different types of floor system observed during the field survey is shown in Fig. 2.103.

(a) Cement flooring

(b) Floor system

Figure 2.103: Floor system in Assam-type buildings

2.6.4.3 Roof Geometry and Systems

The roofing system of the Assam Type buildings is either Gable or Hipped roofs due to high amounts of rainfall in the regions of their prevalence. The traditional roofing material used is 'thatch" (rural areas) and nowadays it is replaced with lightweight CGI sheets. In general, two of the most common roof systems are A-frames and the king-post truss with braces, depending on the span of the roof.

(a) Gable roof with Thatch

(b) Gable roof with GI sheets

(c) Hipped roof with GI sheets

(d) A-frame with tie beam
(Ikra reeds in Gable end)

(e) King post truss with braces

(e) King-post truss

Figure 2.104: Roof geometry and systems in Assam-type buildings

The roof system consists of (i) rafters, (ii) purlins, (iii) king posts, (iv) tie beams, and (v) ridge beams. Collar ties and additional braces are at times provided in case of large rafter length (greater than 3 m). The rafters (0.15 m diameter) are made of wooden logs that are locally available and the spacing between rafters ranges between 0.6-0.7 m. The purlins made of bamboo are attached to rafters that are spaced at 0.3 m. The thatch roofing commonly observed in Assam-type buildings is made of ikra reeds. The pitch of the sloped roof is about 2 m. The slope of the roof varies from one-third to one-fifth of the span depending upon the permeability of the roofing material. Thatched roofs have steeper slopes than tin sheet roofs. However, in recent times, timber rectangular elements are used to form the roof truss with purlins (0.1 m × 0.075 m) nailed to rafters (0.075 m × 0.15 m) and rafters nailed to ridge beam of (0.15 m × 0.15 m). The tie beams are connected to the top plate by C-type joints and the rafters are connected with the help of grooves and nails. No cross-bracings were observed in the roof truss. The photographed images of the roof system taken during the survey are shown below in Fig. 2.104. The typical sketch of the roof system is shown in Fig. 2.105.

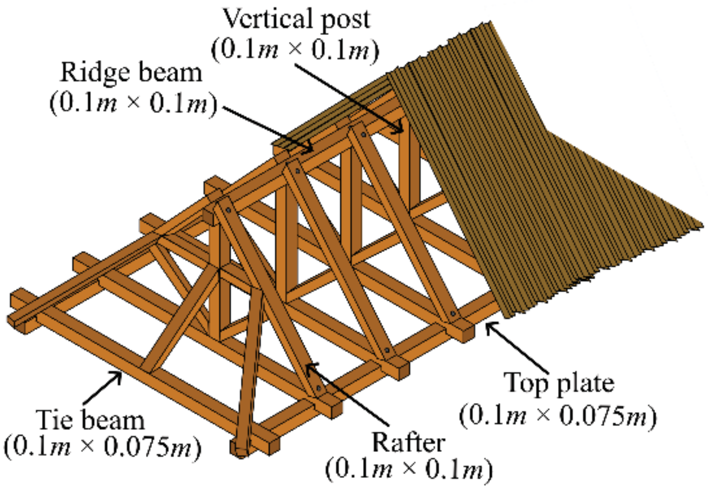


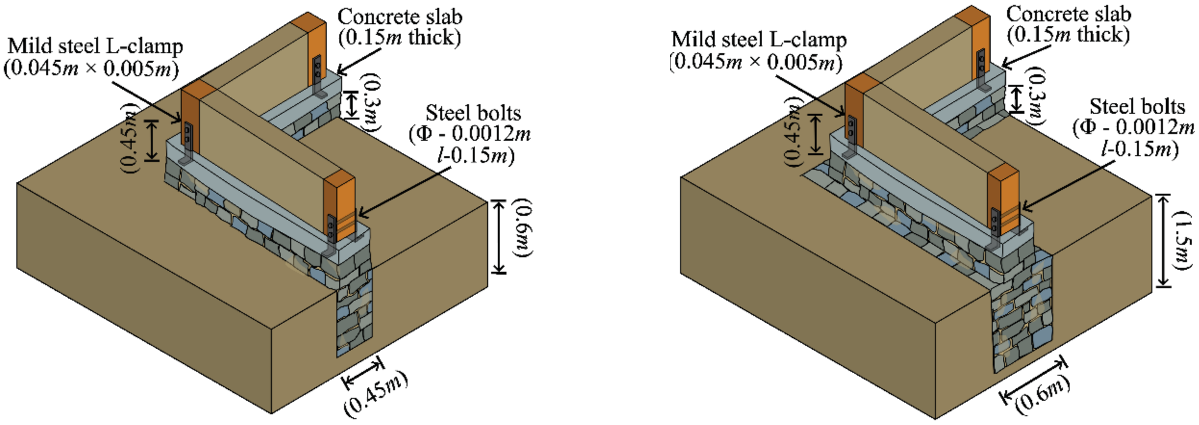
Figure 2.105: Typical sketch of the roof system in Assam-type buildings

2.6.4.4 Soil Conditions and Foundations

The foundation system for Assam-type buildings is the shallow foundation. The vertical posts are inserted into the ground for a distance of 0.6-0.9 m. In recent times, vertical posts are attached to concrete pedestals using iron clamps. In a few buildings, the vertical posts are supported on brick masonry or plain concrete pillars that are raised to the plinth level. The vertical posts are connected to the pillars through steel bolts and U-clamps (Fig. 2.106). In new Assam-type buildings, R.C.C. foundations as per design, with a depth of the foundation of 1.0 m from the ground level and well-connected RC plinth beam as per design were also found during the field survey. The typical sketch of the foundation of Assam-type buildings is shown in Fig. 2.107.

(a) Masonry foundation (b) Post-bolted to foundation

Figure 2.106: Foundations and their connections to post in Assam-type buildings



(a) Foundation on hard soil (b) Foundation on soft soil

Figure 2.107: Typical sketch of the foundations in Assam-type buildings

2.6.5 Visual Conditions and Maintenance

In Assam-type buildings, deterioration is often observed at various locations of the building, due to poor workmanship and quality of timber, joinery, and mortar, and due to the corrosion in nails and steel clamps at the foundation level. One of the reasons for such deterioration in Assam-type buildings is the cyclic wetting and drying of different materials over the season. The construction of arrangement of vertical posts in Assam-type buildings over the stone/masonry brick infills protects them from ground moisture and increases their lifespan. Due to such simpler construction practices, Assam-type buildings require less maintenance and are easy to repair in case of damage or deterioration. The conditions of the Assam-type buildings when surveyed were found to be average to good. The mud plaster in the walls of Assam-type buildings cracks frequently and required regular maintenance (Fig. 2.108). In the case of regions subjected to floods, buildings are protected from water as buildings rest on stilts. In recent times, concrete columns are also used hence timber elements are well protected from water penetration. CGI sheets need maintenance and replacement as Assam and Meghalaya are prone to high rainfall.

(a) Plaster deterioration (b) Plaster deterioration

Figure 2.108: Visual conditions of Assam-type buildings

2.6.6 Contemporary Modifications

This traditional housing is found confined to rural areas, however, a significant percentage of this type of housing is also found in the sub-urban and semi-urban areas of the region. It has been observed that this traditional housing has been slowly replaced by masonry and RC buildings. There has been a legal ban on the cutting of trees, which has reduced the supply of timber as a building material. This situation has forced or encouraged masonry constructions for smaller houses and RC frames for larger or multi-storied houses. Nowadays, traditional Assamese houses coexist along with RC or masonry constructions that have become more popular. RC slabs, GI sheets, heavy masonry infills, and RC columns in place of stilts are found widely nowadays in Assam (Fig. 2.109). However, such modifications in Assam-type should be implemented with caution.

(a) RC Columns

(b) Timber frame and bricks

Figure 2.109: Influence of contemporary materials in Assam-type buildings

2.6.7 Past Seismic Performance and Vulnerability

The investigations conducted in this study suggest the origin of the Assam-type construction at least 2-3 centuries or even more before the present time. However, the exact age of these buildings is unknown. The Himalayan region where Assam-type buildings are prevalently faced several strong earthquakes in the past few centuries. A few of these earthquakes include the 1720 and 1897 Assam earthquakes (Mw=8.1), the 1950 Assam earthquake (M=8.6), and the 2011 Sikkim earthquake (Mw=6.9). Jain (1998) reported the devastation caused by this earthquake led to the development of Assam-type buildings which later became popular in the entire northeast and which is known for their excellent earthquake resistance. Many of these Assam-type buildings are standing as it is from the past century, and no past damage has been reported specific to Assam-type buildings. Post-earthquake surveys and studies in the region of their prevalence show that the Assam-type buildings have performed extremely well. The traditional Assam Type houses did not suffer any structural damage during the past earthquakes and the majority of the Assam-type buildings survived the last two big earthquakes in 1897 and 1950 (Kaushik and Babu 2009). During the 2011 Sikkim earthquake, several reinforced-concrete buildings collapsed and the only damage that occurred to the Assam-type houses was the failure of 2 classrooms in 3rd story of a school building. One of the important observations drawn from the 2011 Sikkim earthquake was that the Assam-type buildings may not be suitable for multi-story buildings (Kaushik and Babu 2009).

The features that could increase the seismic vulnerability of Assam-type buildings are when they are located on slopes. When located on slopes, the unequal length of vertical posts could introduce torsion in buildings, resulting in an increase in seismic forces on the houses. The torsion can also be experienced when complex plan shape (L-, T- etc.) buildings are built. The buildings where the vertical posts directly rest on to the ground without provision of any foundation can be significantly affected by the ground settlements and resulting permanent lateral sway of the building. The provision of electricity to Assam-type buildings also adds to the risk of fire (short-circuit during earthquakes), especially in thatched roofing is used. The roofing system in the Assam-type building is not seen with the presence of any cross-bracings thus it is expected to act as a flexible diaphragm. Poor connections that exist between roof-to-wall connections can cause the failure of rafters and purlins leading to truss failure.

2.6.8 Earthquake-Resilient Features

Assam-type buildings possess several earthquake-resilience characteristics in their siting, architectural, and structural features that are summarized in Fig. 2.110. Starting from the site selection, these buildings are constructed on flat terrain to avoid the plan and elevation irregularities that could arise when sited on slopes or a topographic feature. The selection of rectangular plan shapes and continuity of the elements from the bottom to the top ensures a cuboid shape of these buildings. The building plan aspect ratio of Assam-type houses does not exceed 2. The Assam-type buildings have small sizes of door and window openings placed symmetrically with horizontal struts provided at the sill and lintel levels. The Timber framing around door and window openings further prevent corner stresses. The Assam-type buildings do not have large horizontal projections and hence they do not pose any threat for the falling hazard under earthquakes. These buildings are further constructed in isolation; thus, the possibility of pounding failure is also not expected in Assam-type buildings.

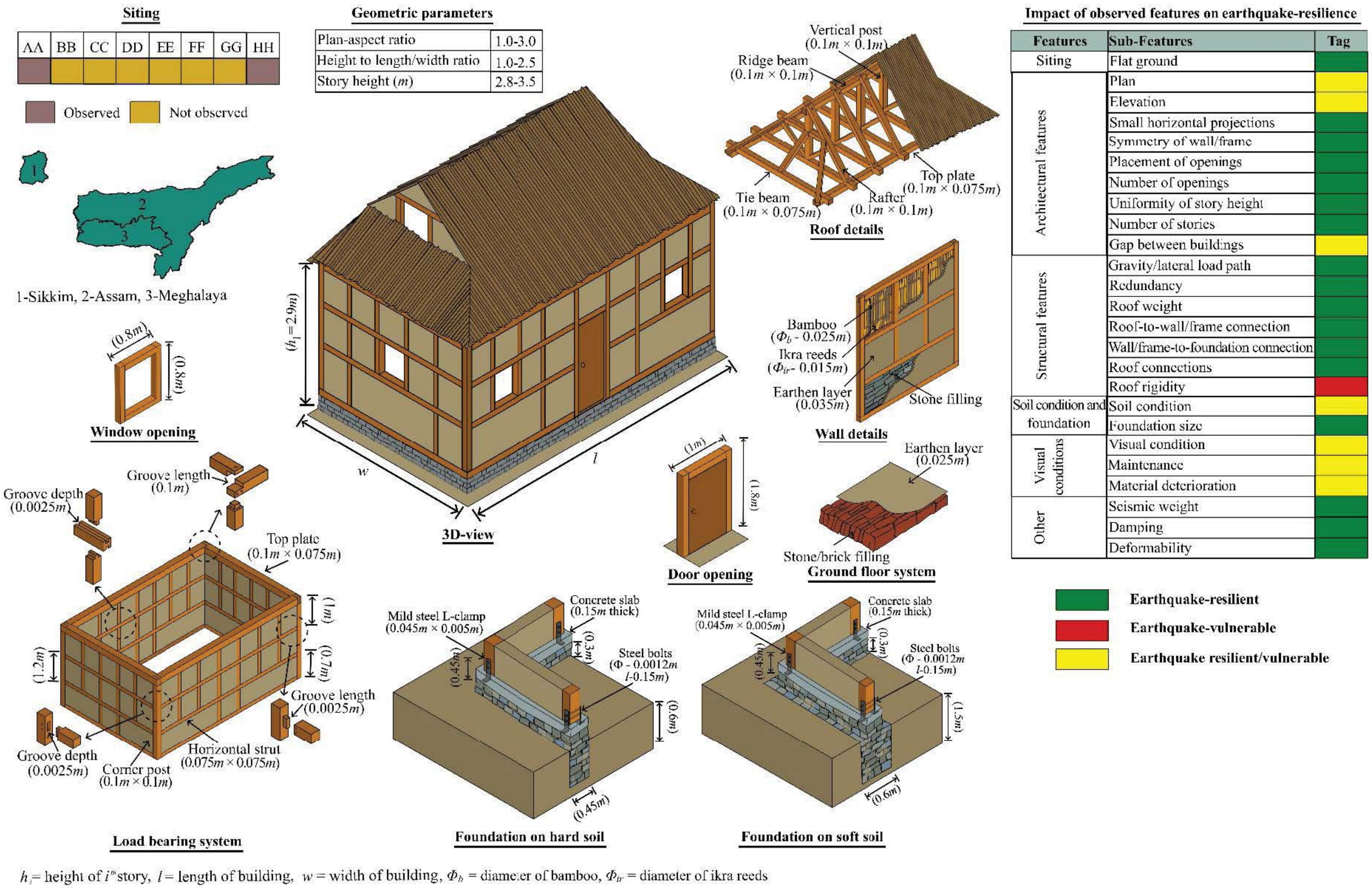
Assam-type buildings have a complete load path to transfer both horizontal and vertical forces to the ground. There is a well-defined, symmetrical, and continuous load path for the flow of inertia forces from the wall to the vertical post, and from vertical posts to foundations with appropriate box action assisted by the hipped roof. These buildings make use of lightweight construction materials for walls and utilize thinner walls. The absence of diagonal timber members in walls makes the Assam-type frame system flexible under lateral loading, due to which these houses attract lesser seismic loads. The presence of a relatively lesser number of members at each joint (in comparison to the other timber frame system, e.g., Dhajji-Dewari) reduces the chances of joint failure, which is important for the overall seismic performance of timber frame housing system under seismic actions. Additionally, the use of flexible (loose-fit) connections between the horizontal and vertical studs improves the overall deformability of the frame under the lateral loads which are necessary for energy dissipation under earthquakes.

The experimental results on lateral load behavior of traditional Assam-type buildings (Chand et al. 2019) showed that these buildings can undergo high lateral deformation without undergoing major damage due to their typical framing system, flexible joints of framing members, and lightweight infill (Ikra) walls. As the vertical posts in Assam-type buildings are not inserted into the foundation, it reduces the chances of failure of post-to-foundation connections. Additionally, these connections between the main wooden posts and foundations are such that they allow rotation in one direction, whereas they restrict in the other direction. The Ikra panels in these buildings do not damage the surrounding timber frame even at large lateral drifts because of their lightweight and flexible connection with the timber frame. Chand et al. (2019) reported that ikra infill in walls did not suffer any visible damage and helped to maintain the stability of the timber frame at large lateral drifts (upt0 a drift ratio of 8.4%). The experimental investigation on the ikra-infilled timber frame showed a significant influence of ikra panels on the lateral strength, stiffness, energy dissipation, and overall lateral load behavior of Assam-type buildings. The cyclic tests on Assam-type timber framed walls showed that the load-carrying capacity of walls with window openings remained more or less constant up to a drift level of up to 8.4% and incurred very little damage. Contrarily, the timber-framed wall with a door opening showed major damage during monotonic loading (at a high lateral drift of 12%) due to insufficient connection of the doorpost with the foundation.

The experimental investigations (Chand et al. 2020) on the connection of Assam-type buildings showed that the connections of all primary joints during cyclic loading remained intact, and the damages were limited even after going for large deformations. The performance of these joints was influenced by the steel elements present in the joints, the development of gaps between timber, and holes and bolts. These connections were able to sustain the pull-out action of vertical posts of timber-frame houses under the lateral loading which in turn enhances the lateral behavior of these houses. As the connections in such timber-framed buildings govern the overall lateral load behavior of Assam-type houses, the connections of primary framing members result in very high lateral drift and deformability as compared to other traditional building typologies.

2.6.9 Suggested Seismic Safety Measures

As discussed in the previous section, the roofs of the Assam-type buildings are expected to behave as flexible diaphragms. Therefore, to improve the in-plane rigidity of the roofs, the necessary measures for the Assam-type buildings are suggested and shown in Fig. 2.111. The rigidity of the roof system in Assam-type buildings can be improved by timber/metal diagonal bracings connected to the existing roof. Further, new buildings of this type can be constructed with an appropriate connection between the timber frame and the foundation.



Siting

AA	BB	CC	DD	EE	FF	GG	HH
🟫	🟨	🟨	🟨	🟨	🟨	🟨	🟫

🟫 Observed 🟨 Not observed

1-Sikkim, 2-Assam, 3-Meghalaya

Geometric parameters

Plan-aspect ratio	1.0-3.0
Height to length/width ratio	1.0-2.5
Story height (*m*)	2.8-3.5

Impact of observed features on earthquake-resilience

Features	Sub-Features	Tag
Siting	Flat ground	🟩
Architectural features	Plan	🟨
	Elevation	🟨
	Small horizontal projections	🟩
	Symmetry of wall/frame	🟩
	Placement of openings	🟩
	Number of openings	🟩
	Uniformity of story height	🟩
	Number of stories	🟩
	Gap between buildings	🟨
Structural features	Gravity/lateral load path	🟩
	Redundancy	🟩
	Roof weight	🟩
	Roof-to-wall/frame connection	🟩
	Wall/frame-to-foundation connection	🟩
	Roof connections	🟩
	Roof rigidity	🟥
Soil condition and foundation	Soil condition	🟨
	Foundation size	🟩
Visual conditions	Visual condition	🟨
	Maintenance	🟨
	Material deterioration	🟨
Other	Seismic weight	🟩
	Damping	🟩
	Deformability	🟩

🟩 Earthquake-resilient

🟥 Earthquake-vulnerable

🟨 Earthquake resilient/vulnerable

h_i = height of i^{th} story, l = length of building, w = width of building, Φ_b = diameter of bamboo, Φ_{ir} = diameter of ikra reeds

Figure 2.110: Summary of key features in Assam-type buildings

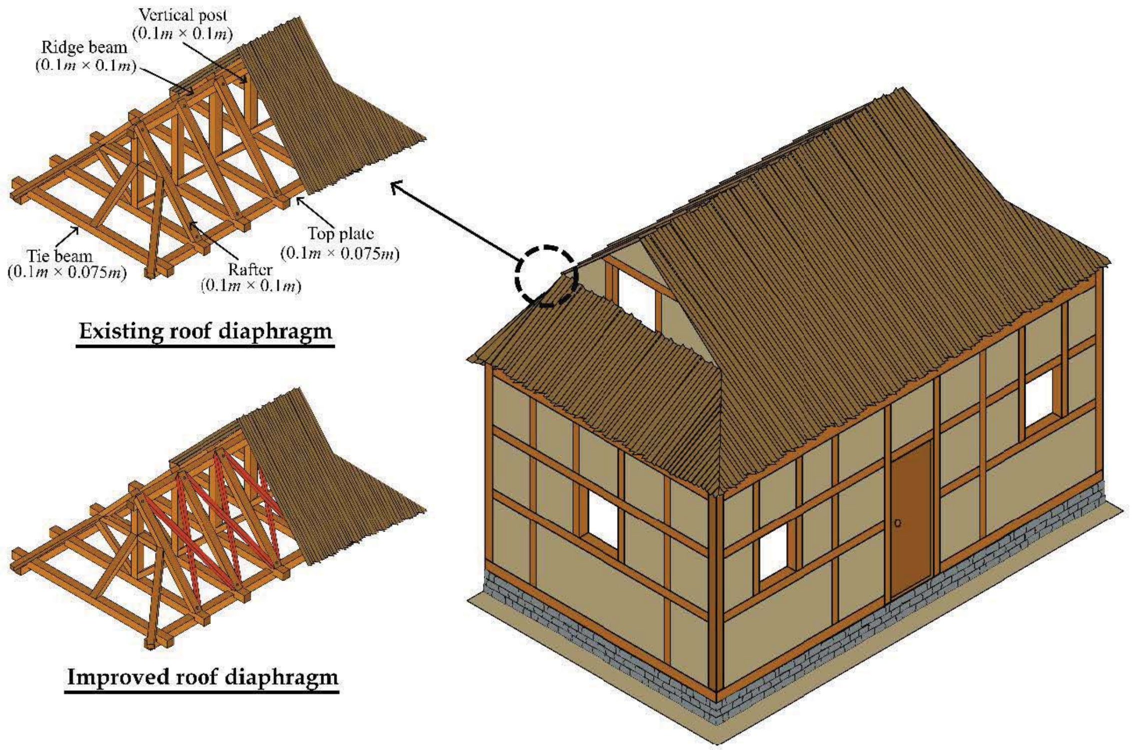


Figure 2.111: Summary of key features in Assam-type buildings

CHAPTER 3

EARTHQUAKE-VULNERABLE TRADITIONAL BUILDINGS

3.1 General Description

The literature (Sood et al. 2013a, b) suggests the existence of earthquake-vulnerable traditional building practices of the North-western Himalayas (within India). One of these practices includes the rammed earth buildings prevalent in the Spiti valley and Ladakh (Sood et al. 2013b). Drystone buildings in Himachal Pradesh and Stone Masonry buildings in Mud Mortar prevalent in Uttarakhand, Himachal Pradesh, and Jammu and Kashmir are the other building practices that have been reported highly seismically vulnerable during several past earthquakes. However, these buildings are not centuries older; hence, the detailed investigations in this Chapter are limited to the rammed earth buildings. A random sample-based field survey approach has been used to identify the earthquake-vulnerable traditional building practice prevalent in the study region. Extensive field surveys have been conducted in the study region, and more than 50 traditional buildings were surveyed within the study region. The details of the prevalent (existing) traditional earthquake-vulnerable building practices in terms of their siting, architectural features, structural features, soil conditions, foundations, and visual conditions were collected from the field surveys. The corresponding detailed sketches are developed. As a part of the field surveys, discussions with the locals were also carried out to learn more about the behavior of these buildings during past earthquakes and the maintenance required for such buildings. The photographs captured during the field surveys and their detailed relevant discussions are presented subsequently.

3.2 Rammed Earth Buildings

3.2.1 Introduction

Rammed earth buildings can often be observed in and around the Spiti river valley of the ‘Lahaul and Spiti’ district in the state of Himachal Pradesh and also in the union territory of Ladakh (Fig. 3.1). This rammed earth building typology (also referred in the literature as ‘Spitian Architecture’) originated from the Buddhist culture (Dhammajoti 2022). This typology is specific to this region, which is a mountainous desert area, where the rammed earth is available in abundance whereas other natural construction materials such as stone and timber are available in scarcity. The rammed earth construction is the oldest traditional construction practice of the Spiti Valley region and is still being practiced in this region even for the newer constructions. One of the oldest examples of the traditional rammed earth construction, which still exists in the region, is the ‘Key Gompa Monastery’ (Fig. 3.2), built approximately 1000 years ago. Rammed earth construction is prevalent in the rural areas of Lahaul and Spiti district of Himachal Pradesh, including the villages Lasar, Hansa, Kyato, Shego, Lidang, Sichling, Lari, and Somra on the Manali to Kaza route, Rumtse, Miru villages in the union territory of Leh on Manali to Leh route, and Nimmu, Nurla, Lamayaro, Haniskot, and Chaukhiyal union territory of Ladakh on Leh to Srinagar route. According to India’s current seismic zonation map (BIS 2016), these villages fall in the seismic zone IV. In addition, these regions are further characterized by mild-to-moderate slopes. The walls of the building are made up of rammed earth, with stones used for the construction of their foundations, raised platform, and bamboo/ timber along with mud used for the construction of floors and roof systems.

Figure 3.1: Map showing the regions of the prevalence of rammed earth buildings

(a) key Gompa Monastery view

(b) key Gompa Monastery close view

Figure 3.2: Rammed earth buildings on hill slopes in Spiti Valley – Key Gompa Monastery

3.2.2 Siting

The presence of mild-to-steep slopes characterizes the regions of the prevalence of rammed-earth buildings (Fig. 3.3). Thus, many rammed-earth buildings are constructed on slopes and sometimes even on the top of a hill (Fig. 3.2(a)). The typically observed siting in the rammed earth buildings include: (i) buildings resting on flat ground (Fig. 3.4(a)-(b)), (ii) buildings with a raised platform of stone masonry approximately upto a height of 0.6-1.0 m (Fig. 3.4(c)), (iii) buildings with two different founding levels (Fig. 3.4(d)-(e)), and (iv) buildings following the natural slope of the ground (Fig.

3.4(f)). The observed slope gradient does not exceed 3:1 (H: V) for buildings constructed on sloping ground.

(a) Spiti valley (b) Leh

Figure 3.3: Prevalence of low-rise rammed earth construction in Spiti valley and Leh

(a) On flat ground (b) On flat ground

(c) On the raised stone platform (d) Two foundation levels

(e) Two foundation levels (f) On sloping ground

Figure 3.4: Different siting of rammed earth buildings

3.2.3 Architectural Features

Various building plans and elevation shapes can be seen in the Spiti valley and Ladakh for the rammed earth construction. Usually, most of the rammed earth buildings are constructed, ignoring the fundamental principle of earthquake safety, i.e., without maintaining regularity in plans and elevations (Fig. 3.5). As a result, except a very few buildings (Fig. 3.5 (a)-(c)), many rammed earth buildings are seen with the plan and elevation irregularities. The commonly seen elevation irregularity include setbacks in their elevation (Fig. 3.5 (d)), and widely seen plan irregularities include the presence of re-entrant corners in the building plan (Fig. 3.5 (e)).

(a) Rectangular plan (b) Rectangular plan

(c) Rectangular plan (d) Setback building

(e) Re-entrant corner (f) Re-entrant corner

Figure 3.5: Plan and elevation shapes in rammed earth buildings

Rammed earth buildings are mainly used for residential occupancy, with an average plan area typically between 50-75m2. The lengths and widths of the building usually vary between 4-10 m, with the plan aspect ratio between 1.2-2.75. The average story height in rammed earth construction typically ranges between 2.5-3.2 m, which is somewhat comparable to the story heights in modern structures. Most of the rammed earth buildings are one-storied with few exceptions, where two or sometimes even three stories are also seen (Fig. 3.5). The rammed earth buildings in the region are characterized by significant variations in terms of the extent of openings provided for doors and windows in different buildings (Fig. 3.6). The maximum openings in walls of this construction have been observed to vary between 15%-75% of the length of the wall, with a usual concentration of openings in one of the building directions and also in one of the walls (i.e., more openings provided at the front face of the building). There were no projections observed in both vertical or horizontal directions. Further, rammed earth buildings are constructed with a sufficient distance between adjacent buildings and do not share walls with the neighboring buildings in rural areas (Fig. 3.7(a)). However, in densely populated areas (e.g., Leh), some buildings in close proximity were also seen (Fig. 3.7(b)).

(a) Small openings

(b) Small openings

(c) Small openings

(d) Moderate openings

(e) Large openings

(f) Large openings

Figure 3.6: Openings in rammed earth buildings

(a) Gap between buildings (b) Closely spaced buildings

Figure 3.7: Distance between two adjacent rammed earth buildings

3.2.4 Structural Features

3.2.4.1 Load-bearing Wall/Frame System

Rammed earth buildings have load-bearing walls made of rammed earth locally available in the Lahaul and Spiti, and Leh regions. The bottommost portion (approximately 0.60-1.0 m high) of walls in rammed earth buildings is a raised platform made up of field stones (Fig. 3.8) to prevent direct contact of walls with heavy snow cover in the region during the winter season. The gravity and lateral loads are expected to be resisted by the load-bearing rammed earth walls. These rammed earth walls possess very little tensile (bending) and shear strength. Two different wall thicknesses were observed for the rammed earth construction in the study region. The centuries-older rammed earth building walls have a thickness of 0.40 m (Fig. 3.8), whereas; the relatively newer rammed earth building walls are 0.35 m thick (Fig. 3.8), thus, resulting in a height-to-thickness ratio of walls between 6.5-9. Rammed earth buildings have at least three walls in each horizontal direction, and the computed plan density of structural walls varies between 15-25%. The external and internal faces of walls are usually plastered using the Spiti river mud that exhibits good insulating properties. These rammed earth walls are constructed in lifts along the height, with each lift being approximately 0.30 m high. Therefore, the horizontal layering between two individual courses of walls is visible (Fig. 3.8(a)). It is seen that the wall-to-wall joints in rammed earth buildings are not staggered (Fig. 3.9) in the successive lifts along the height in the orthogonal walls, and in a few buildings, separation in the form of vertical cracks (Figs. 3.9(a)) can be seen at the wall-to-wall junctions.

(a) Wall thickness @ 0.35 *m* (b) Wall thickness @ 0.40 *m*

Figure 3.8: Load-bearing walls in rammed earth buildings

In a few buildings, the wall-to-wall connections in rammed earth construction are established using Ashlars (Figs. 3.9(b)) and a lintel-level RC band. The typical sketch depicting the rammed earth wall and the wall-to-wall connection is shown in Fig. 3.10.

(a) Unstaggered wall joint

(b) Use of ashlar and RC band for wall-to-wall connections

Figure 3.9: Wall-to-wall joints in rammed earth buildings

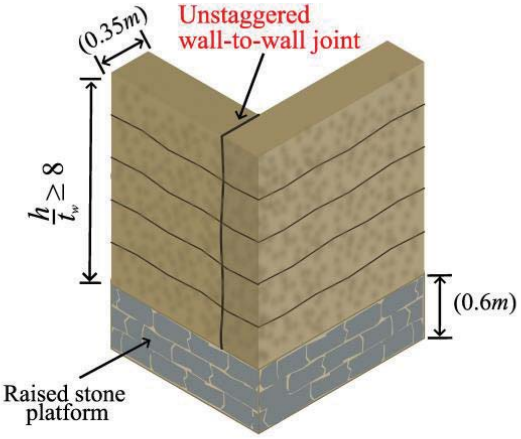


Figure 3.10: Typical sketch of walls in rammed earth buildings

3.2.4.2 Floor Systems

In the case of single-story buildings, the floor has been observed to be mostly stone and earth-filling, usually covered with mud slurry (Fig. 3.11). However, in the case of multi-story buildings, split timber elements, and wooden/bamboo beams are inserted into the walls covering the full thickness of the wall, but without any positive connections. The plastic or jute bags are overlaid on split timber elements and wooden/bamboo beams over which a thick layer of mud is placed. The floor system is not tied together with the walls. The floor system does not include any provisions for cross-bracings. Thus, the floor system in rammed-earth buildings is expected to behave as flexible floor diaphragms. The typical sketch of the floor/roof system in rammed earth buildings is shown in Fig. 3.12.

3.2.4.3 Roof Geometry and Systems

The region where rammed earth construction is practiced is characterized by desert area; thus, flat roofs (Fig. 3.13(a)-(c)) are often seen with a few exceptions of sloped roofs (Fig. 3.13(d)). The two of the most commonly used roofing materials in rammed earth construction include flat earthen roofs (Fig. 3.13(a)-(c)) and CGI sheets (Fig. 3.13(d)). In the case of flat roofs, closely spaced split timber elements, and wooden/bamboo beams (at equal intervals) are embedded in the rammed earth walls in two orthogonal directions (Fig. 3.14(a)-(c)), without any positive connection or arrangement to tie them with the walls. Plastic/jute bags are placed over timber/bamboo girders, on which a 0.05 m thick mud overlay (earthen) is provided (Fig. 3.12). The presence of cross-bracings has not been observed in the roof systems of rammed earth buildings; thus, roofs are expected to behave as flexible diaphragms. The flexibility of the floor and roof system does not restrain the rammed earth walls. Therefore, these rammed earth walls behave as vertical cantilevers and are susceptible to failure under out-of-plane action.

(a) Earthen floor (b) Earthen floor

Figure 3.11: Mud/Earthen floors in rammed earth buildings

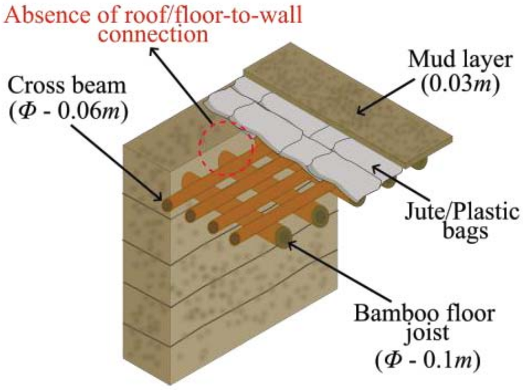


Figure 3.12: Typical sketch of the floor/roof system in rammed earth buildings

3.2.4.4 Soil Conditions and Foundations

In rammed-earth construction, there are strip footings of locally available river/field stones (Fig. 3.15). The stone foundations are raised to 0.6-1.0 m above the ground level to prevent wall contact with water splashes and snow cover. The width of the foundation is equal to the thickness of the wall (0.40 m) and 1.5 times the thickness of the wall (0.60 m) for buildings resting on rock and soft soil, respectively. The depth of the footing depends upon the property of the soil strata. In the case of rocky strata, the depth of the foundation ranges between 0.3-0.6 m, and in the case of soft soil stratum, the depth of the foundation varies between 1.0-1.5 m (Fig. 3.16). The discussions with locals further revealed that no specific measures are taken in the rammed earth building to connect the building with its foundation.

3.2.5 Visual Conditions and Maintenance

The visual conditions of most buildings of rammed earth type have been observed to be average to good, with few buildings that were heavily deteriorated. The house owners do the maintenance of these buildings. The exteriors and interiors of these buildings are periodically coated with mud slurry, with the frequency of interior coatings being almost three-to-four times per year. A few buildings with severe cracks at the junction of walls with overall deteriorated/damaged conditions were also seen (Fig. 3.17).

(a) Flat roof with mud cover (b) Flat roof with mud cover

(c) Flat roof with mud cover (d) Sloping roof with CGI sheets

Figure 3.13: Roofing materials in rammed earth buildings

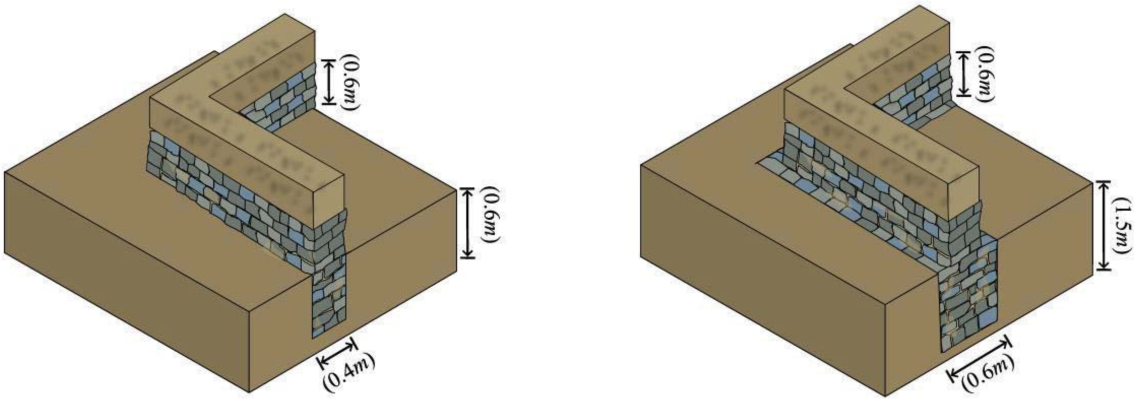
(a) Bamboo and split timber elements (b) Bamboo and split timber elements

(c) Bamboo and split timber elements (d) Bamboo girders

Figure 3.14: Floor/Roof systems in rammed earth buildings

(a) 0.45m thick stone foundation (b) Stone foundation

Figure 3.15: Foundations in rammed earth buildings



(a) Foundation on hard soil (b) Foundation on soft soil

Figure 3.16: Typical sketch of foundations in rammed earth buildings

(a) Deteriorated building (b) Demolished building

Figure 3.17: Deteriorated rammed earth buildings in the study region

3.2.6 Contemporary Modifications

Nowadays, a few features of contemporary practices are also seen in the rammed earth buildings. These contemporary modifications include structural steel I-girders in the roof supporting system, ashlars, and RC bands (Fig. 3.18).

3.2.7 Past Seismic Performance and Vulnerability

The investigations conducted in this study suggest the origin of the rammed earth buildings several centuries (at least more than 10) before the present time. The Himalayan region, where rammed earth buildings are prevalent, has faced several strong earthquakes since the origin of the rammed earth construction. A few of these earthquakes include the 1720 Kumaun earthquake (M>8), the 1803 Garhwal earthquake (Mw=8.1), the 1897 Assam earthquake (Mw=8.1), the 1905 Kangra earthquake (Mw=7.8), the 1934 Bihar Nepal earthquake (Ms=8.1), the 1950 Assam earthquake (M=8.6), the 1975 Kinnaur earthquake (Ms=6.8), the 1991 Uttarkashi earthquake (Mw=6.8) and the 1999 Chamoli earthquake (Mw=6.6). When asked about the performance of the rammed earth buildings, the occupants recollected and replied that the region was not subjected to any significant earthquake event in the recent past. However, during the 1975 Kinnaur earthquake (Ms=6.8), the damage was reported in rammed earth buildings, monasteries, and temples. It had been reported (Singh et al. 1977) that rammed earth buildings got wide cracks in the walls (in a radius of 100 Km from the epicenter). Under this earthquake, many rammed earth buildings tilted and collapsed.


(a) Steel girders (b) Steel girders


(c) Steel girders (d) RC band

Figure 3.18: Influence of contemporary materials in rammed earth buildings

The rammed earthen buildings in the study region possess many earthquake-vulnerable characteristics in their siting, architectural, and structural features, as shown in Fig. 3.19. Starting from the site selection, many buildings in the study region are constructed following the natural slopes of the ground, with two foundation levels, and sometimes even at the top of a hill. In particular, the building built on slopes has an irregular stiffness distribution in the building plan that is likely to induce torsion, mainly in the direction across the slope. A building with two different levels of foundations has especially two stories with significant differences in the location of the center of masses of different floors along the height and higher masses in the upper story, which can lead to mass irregularity in such buildings. In contrast, the buildings on the top of a hill could be subjected to amplified seismic forces due to topographic amplification effects (Pagliaroli et al. 2015). Further, the slope failure could also lead to the failure of rammed earth buildings built on steep slopes and subsequently lead to the collapse of the building too. These specific siting features are the potential threats to rammed earth buildings under earthquakes.

Like siting aspects, many architectural features in the rammed earth buildings could be considered significantly detrimental to their seismic performance. Few rammed earth buildings are seen with re-entrant corners. The buildings with re-entrant corners are subjected to stress concentration at the junctions of the walls. The story heights in the rammed earth buildings are relatively higher as compared to other traditional building practices of the Himalayan belt, and many buildings exist in the study region that is 2-storied, even though the Indian building code (BIS 1993) permits a maximum of single-story building with an attic space, considering the seismicity of the region. Many rammed earth buildings are characterized by large openings (up to 75% of the wall length) in one of the walls, with some openings that are placed close to the edges. Large openings in one of the walls in rammed earth buildings can induce torsion in buildings, diagonal shear cracking in the wall piers, and, subsequently, the failure of walls. Further, closely spaced buildings in urban areas can also lead to pounding failure of rammed earth buildings.

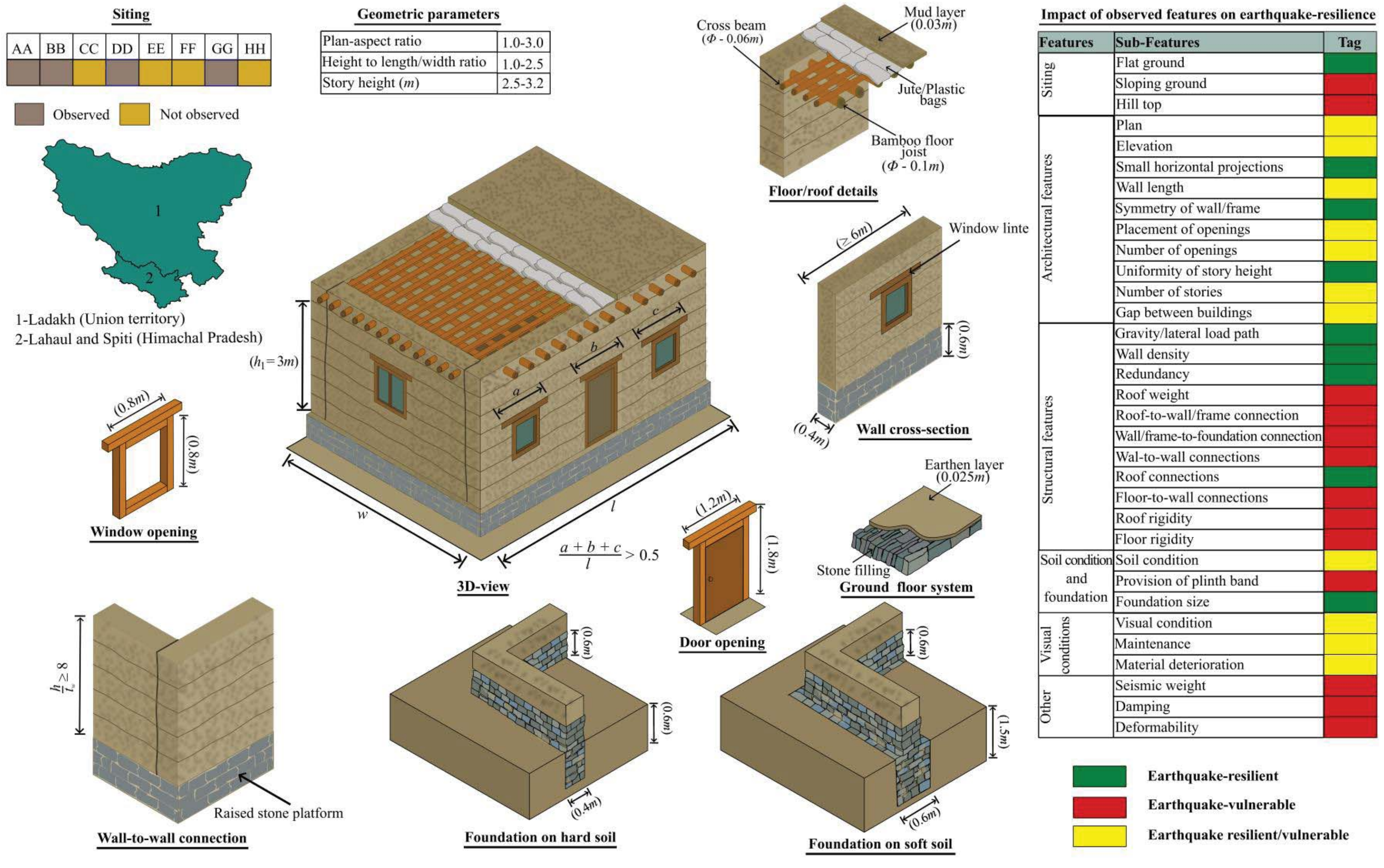
Rammed earth buildings are seen with several structural deficiencies that could lead to the collapse of these buildings under moderate to intense earthquakes. The rammed earth walls, which are primarily the gravity and lateral-load resisting elements, offer multiple deficiencies that include: (i) the use of walls with large horizontal spans (up to 6 m) is seen without the use of buttress or cross-walls, (ii) the wall-to-wall joints are not staggered, (iii) mostly walls are constructed without the provision of continuous bands at the sill, the lintel, and the eave levels, (iv) sometimes walls are very slender, that is their height-to-thickness ratio exceed 8, and (v) low bending and shear strength of rammed earth walls. The presence of these specific features in rammed earth buildings suggests that they will not be able to maintain their integrity and that walls are susceptible to failure in horizontal and vertical bending. The floor and roof system in rammed earth buildings consists of split timber elements or bamboo girders with a thick mud layer and jute bags. Thus, the floors and roofs are heavy-weight. Further, rammed-earth buildings' floor and roof systems have no positive connections with walls. They are constructed without any diagonal bracings that could prevent the relative movement of floors/roofs. Floors and roofs are not tied to the walls. Hence, the floors and roofs in rammed-earth buildings are expected to behave as flexible diaphragms. These flexible floors and roof diaphragm do not expect to offer any restraint to walls, making walls behave as vertical cantilevers, which could lead to wall failure in the out-of-plane direction and, subsequently, the floor/roof collapse. The walls of rammed-earth buildings do not have any connection with the foundations. Heavy-weight floors and roofs in two-storied rammed-earth buildings could lead to overturning (tilting) of the building. In addition, the rammed earth possesses a relatively low damping ratio (3-4% of the critical damping in the undamaged state, Bui et al. 2011) as compared to contemporary materials (e.g., reinforced-concrete, where it is 5% of the critical damping in the undamaged state). The reduced damping ratio increases seismic force demands (up to 20% in contrast to the case when the damping ratio is 5%) on rammed-earth buildings and increases their overall seismic vulnerability. The presented discussion highlights that rammed-earth buildings are highly vulnerable to earthquakes.

3.2.8 Earthquake-Resilient Features

Rammed earthen buildings possess very limited features that are beneficial for their earthquake resistance. Firstly, only a few buildings are seen to be constructed on flat ground. These buildings are primarily rectangular plan, though exception exists. Rammed earth buildings are usually low-rise and have a reasonably low height-to-width ratio. These features can be considered as the features which are good for their earthquake resistance.

3.2.9 Suggested Seismic Safety Measures

As discussed in the previous section, the rammed earth building possesses many earthquake-vulnerable features in their siting, architectural features, structural features, and foundations. It is to be noted that the rammed earth construction is still in practice in the Lahaul and Spiti district of Himachal Pradesh and UT of Ladakh, even for the construction of new buildings. Hence, this study suggests seismic safety measures for existing (Fig. 3.20) and new rammed earth buildings (Fig. 3.21). Detailed safety measures are recommended in Chapter 5.



Siting

AA	BB	CC	DD	EE	FF	GG	HH
🟫	🟫	🟨	🟫	🟨	🟨	🟫	🟨

🟫 Observed 🟨 Not observed

1-Ladakh (Union territory)
2-Lahaul and Spiti (Himachal Pradesh)

Geometric parameters

Plan-aspect ratio	1.0-3.0
Height to length/width ratio	1.0-2.5
Story height (m)	2.5-3.2

Impact of observed features on earthquake-resilience

Features	Sub-Features	Tag
Siting	Flat ground	🟩
	Sloping ground	🟥
	Hill top	🟥
Architectural features	Plan	🟨
	Elevation	🟨
	Small horizontal projections	🟩
	Wall length	🟨
	Symmetry of wall/frame	🟩
	Placement of openings	🟨
	Number of openings	🟨
	Uniformity of story height	🟩
	Number of stories	🟨
	Gap between buildings	🟨
Structural features	Gravity/lateral load path	🟩
	Wall density	🟩
	Redundancy	🟩
	Roof weight	🟥
	Roof-to-wall/frame connection	🟥
	Wall/frame-to-foundation connection	🟥
	Wal-to-wall connections	🟥
	Roof connections	🟩
	Floor-to-wall connections	🟥
	Roof rigidity	🟥
	Floor rigidity	🟥
Soil condition and foundation	Soil condition	🟨
	Provision of plinth band	🟥
	Foundation size	🟩
Visual conditions	Visual condition	🟨
	Maintenance	🟨
	Material deterioration	🟨
Other	Seismic weight	🟥
	Damping	🟥
	Deformability	🟥

🟩 Earthquake-resilient
🟥 Earthquake-vulnerable
🟨 Earthquake resilient/vulnerable

h_i = height of i^{th} story, l = length of building, w = width of building

Figure 3.19: Summary of key features in rammed earth buildings

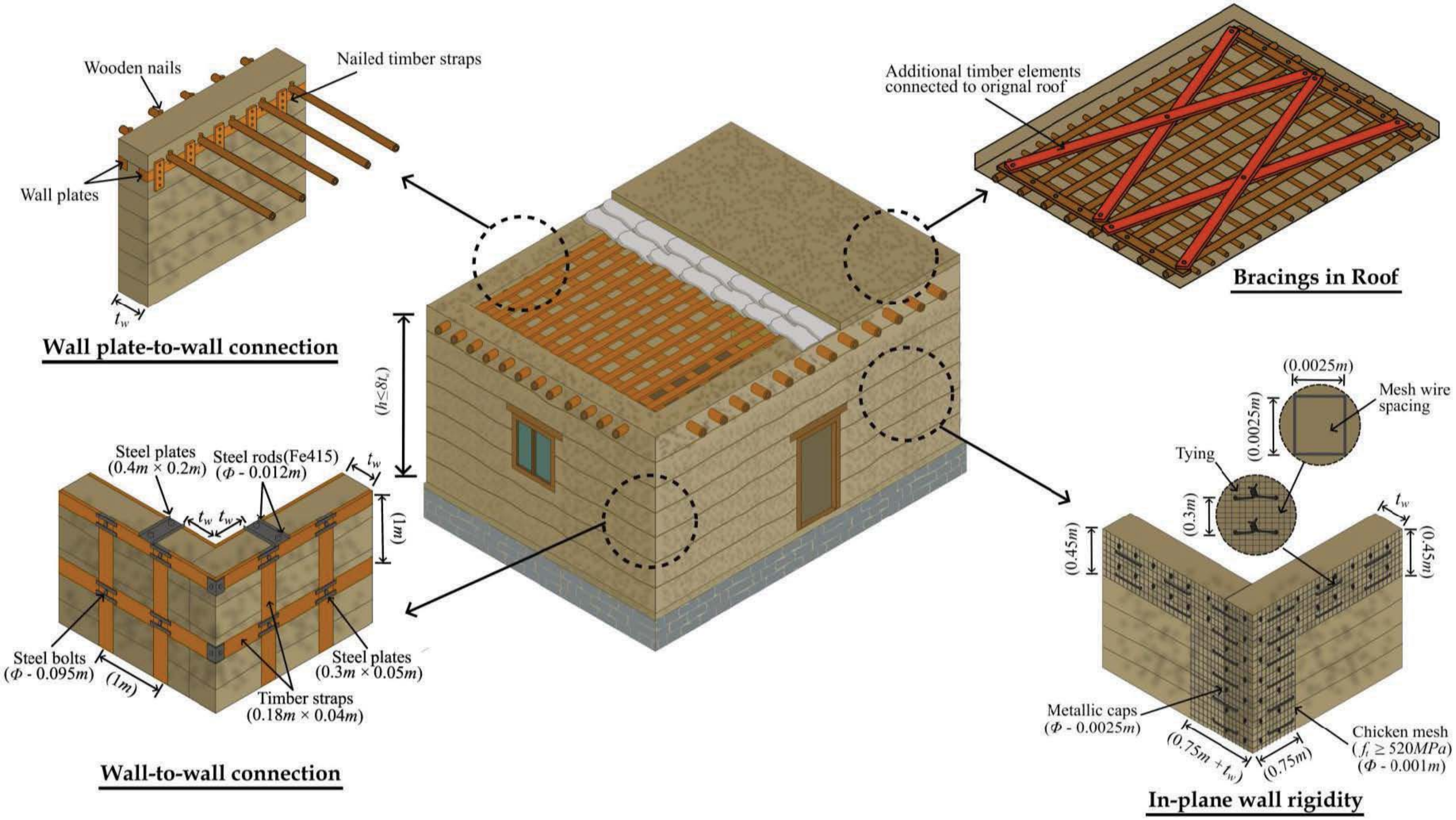
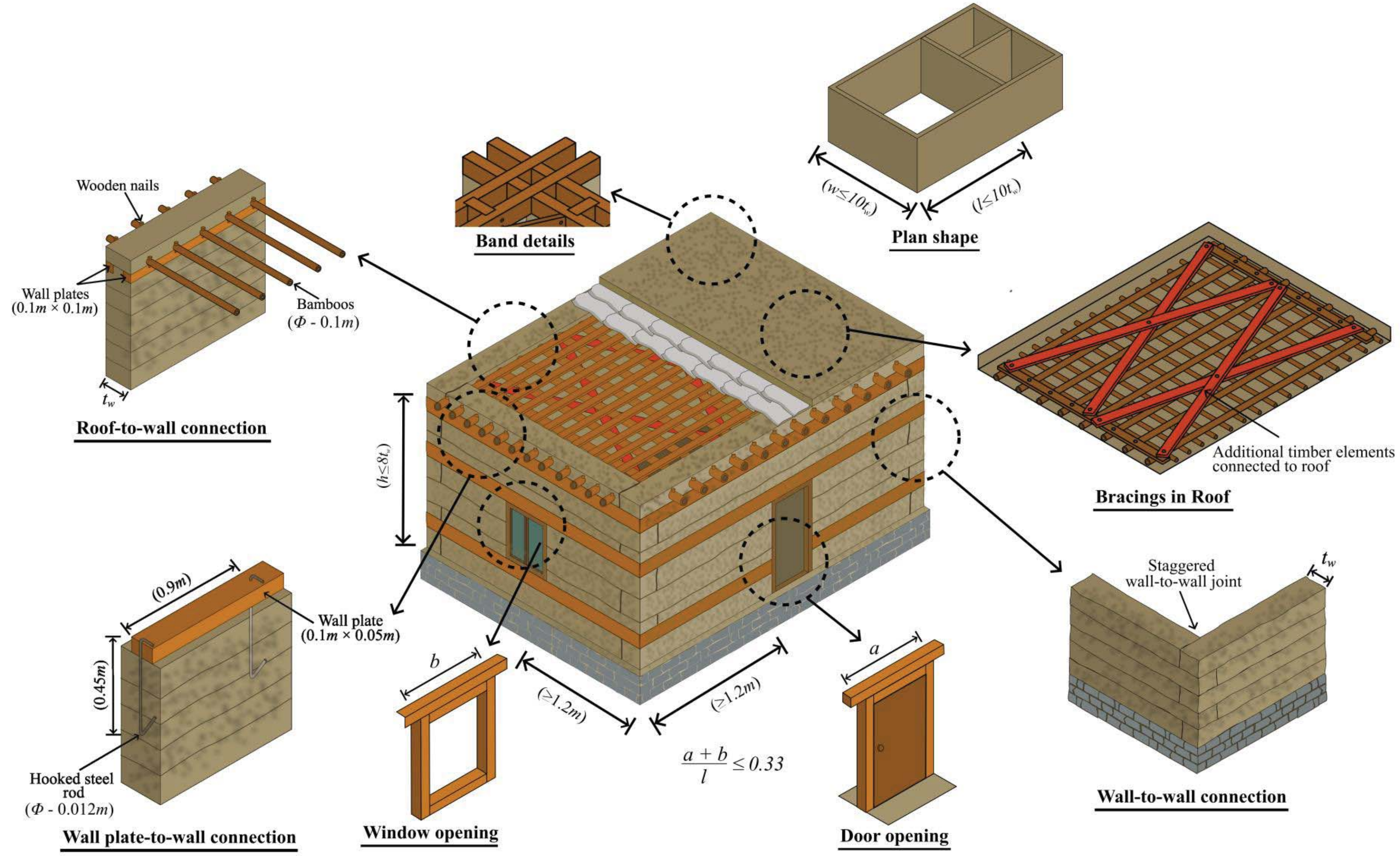


Figure 3.20: Suggested safety measures for existing rammed earth buildings



l = Length of building, w = Width of building h = Height of building t_w= Thickness of wall

Figure 3.21: Suggested safety measures for new rammed earth buildings

CHAPTER 4

STRUCTURAL CLASSIFICATION OF TRADITIONAL BUILDINGS

4.1 General Description

Collecting existing building details and classifying many buildings into practically manageable structural systems based on their siting, architectural, and structural features is an essential step in seismic vulnerability assessment at the regional scale. The classification of many buildings in a city/region/country is achieved by developing a regional classification of structural systems. Several structural system classification schemes/catalogs have already been developed and are available in the literature (e.g., ATC-13 1985; HAZUS 2002; RISK-UE 2003; PAGER-WHE 2008; GEM 2012; NDMA 2013). However, these existing structural system classifications mainly concentrate on contemporary buildings (Lang et al. 2018), and traditional buildings are considered only through coarse classification. As the present study is focused explicitly on traditional buildings, the specific characteristics of the traditional structures observed during field surveys are all considered in developing the structural system's classification.

The existing structural system's classification schemes in the literature make use of a building's essential attributes, including architectural and structural features (gravity- and lateral-load resisting system, building height, floor system, roof system, and foundation system) in distinguishing and classifying buildings that are expected to behave more or less in a comparable manner under earthquake of a given intensity. One of the important limitations associated with the existing structural system's classification schemes is that the classification is prepared considering the building inventory of a specific region. Thus, it does not apply to other areas, as the characteristics of the building stock and construction practices vary from region to region. In addition, the limitations become even more concerning for the areas considered in this study, as the topographic features also affect the seismic performance of buildings.

Most of the study areas considered herein have significantly different terrain conditions (mostly characterized by ridges and valleys) compared to other regions of India and the rest of the world. As discussed, and highlighted earlier in Chapters 2 and 3 of this report, the non-availability of flat land for building construction in the study region results in the construction of buildings on mild-to-steep slopes. The buildings usually follow the natural slope of the ground. Hence severe irregularities are introduced in their plan, elevations, and sometimes even in the arrangement of the foundation. Due to irregularities, a drastic increase in the building's susceptibility to experience damage and loss can be expected while subjected to ground shaking. Therefore, including these siting attributes in developing structural system classification schemes is essential.

During past earthquakes, observed damages in buildings show that the differences in the levels of foundations can significantly damage traditional buildings (Yon et al. 2021). Therefore, to consider the siting of the traditional buildings, elevation shapes are categorized considering the arrangement of a building's foundation on the ground, the slope angle, and the soil/earth retaining system. The categorized elevation shapes are (i) buildings resting on nearly flat ground (i.e., on slopes not exceeding 5 degrees), (ii) buildings resting on a mild-to-moderate slope (i.e., on slopes greater than 5 degrees but not exceeding 30 degrees), (iii) buildings resting on a steep slope (i.e., on slopes exceeding 30 degrees) or sometimes in a deep vertical cut (i.e., a special case of the building resting on a steep slope, with walls of the building in one of the principal directions acting as retaining walls), and (iv) buildings resting on stone masonry platform that helps in achieving conditions identical to the flat terrain. In addition, the other variants of elevation shapes (though seen in very few traditional buildings) are (i) buildings directly supported on timber posts/Tholas and (ii) buildings situated below the road level. The typical sketches of the discussed elevation shapes are shown in Fig. 4.1. Similar to siting, the observed variations in the building heights, lateral load-resisting systems, floor systems, roof systems, and foundations are also considered, and their structural classification is presented.

4.2 Siting of Traditional Structural Systems

Based on the details collected during field surveys, the structural configurations of traditional buildings in the study region are classified based on the arrangement of foundation on slopes, the corresponding slope retaining system (if any), and the building supporting system. Based on the conducted field surveys, the observed structural configurations of the traditional building types are subdivided into eight parent structural configurations, hereafter denoted as configurations AA-HH. The specific details and sketches of these structural configurations are described in Fig. 4.1. It is to be noted that among these eight identified structural configurations, few of them are specific to certain structural systems. In contrast, others have been observed for almost all the traditional structural systems in the study region.

4.3 Heights of Traditional Structural Systems

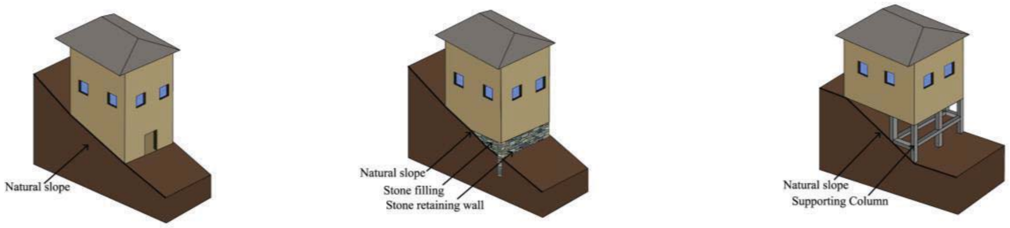
The expected seismic performance or damage in the buildings largely depends on the building height, which is also an indicator of the period of vibration (flexibility) of the structure. Classifying buildings into subclasses based on a structure's height is low-rise, mid-rise, and high-rise. In the case of traditional buildings in the study region, defining the number of stories in a building can be complex and challenging, specifically when buildings are located on slopes, as the number of stories in a building on the uphill side and downhill side differ. Indian Standard (BIS 2016) and earlier studies (Surana et al. 2018) recommend using the building height above the upper ground level to compute seismic design force and to measure the number of stories in such buildings. Consistent with the recommendation mentioned above, in the present study, traditional buildings up to three stories above the upper ground level are defined as low-rise buildings, and traditional buildings with four or five stories above the upper ground level are defined as mid-rise buildings (Table 4.1). It is to be noted that traditional buildings of more than five stories have not been observed in the field surveys; hence, those aren't included in the structural classification.

4.4 Structural Systems of Traditional Buildings

A building's resistance to gravity and lateral loads can be achieved by various actions/types of load-resisting systems. These structural systems include framed systems, load-bearing wall systems, and hybrid systems (i.e., a combination of frame and load-bearing wall systems). Thus, based on the details collected from the field surveys in the study region, the identified structural systems of traditional buildings are classified under three subclasses, i.e., frames, load-bearing wall systems, and hybrid systems (Table 4.1). These structural systems are further used to present the structural classification in the subsequent sections.

A) Building resting on flat ground

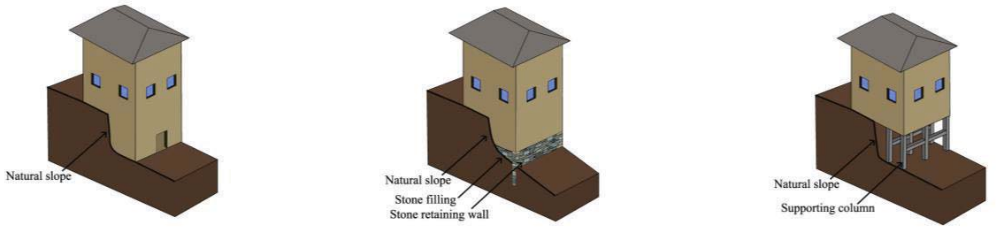
B) Building resting on the flat terrain like ground created by filling soil/stone



C) Building resting on sloping ground

D) Building resting on sloping ground with a retaining wall on the downhill side

E) Building resting on sloping ground with stilts



F) Building resting in deep vertical cut

G) Building resting in deep vertical cut with retaining wall on the downhill side

H) Building resting in deep vertical cut with stilts

Figure 4.1: Typical sketches of the siting in the studied traditional buildings: (a) Building resting on the flat ground, (b) Building resting on the flat terrain-like ground created by filling soil/stone, (c) Building resting on the sloping ground, (d) Building resting on the sloping ground with a retaining wall on the downhill side, (e) Building resting on the sloping ground with stilts, (f) Building resting in the deep vertical cut/steep slope, (g) Building resting in the deep vertical cut/steep slope with a retaining wall on the downhill side, and (h) Building resting in the deep vertical cut/steep slope with stilts

4.5 Floor and Roof Systems of Traditional Buildings

Roofs and floors act as horizontal framing systems in buildings and help in transferring the inertial forces generated in the buildings from the horizontal framing members to the vertical framing members (e.g., frames, load-bearing walls, etc.) and finally to the foundation and the ground beneath. As discussed in Chapters 2 and 3, various floor systems (e.g., wooden planks with floor joists, mud floor, etc.) and roof systems (e.g., flat roofs or sloping roofs on timber frames/truss, etc.) are observed in the study region. Accordingly, these floor and roof systems identified in the study region are also summarized in Table 4.1. These floor and roof systems are further used to present the structural classification in the subsequent sections.

4.6 Structural System Classification of Traditional Buildings

To group the traditional buildings with similar engineering characteristics and expected performance, they are classified using structural system identifiers. This structural system identifier considers all the important structural attributes, including building siting, the number of stories above the upper ground level, the load-bearing system, the floor and roof systems, and the foundation, which primarily controls the expected performance and vulnerability of buildings under earthquakes. Table 4.1 presents the definition of the structural system identifier, which will be used to assign the structural system code to each of the traditional buildings in the study region. The typical examples of the assignment of structural system code are presented in Table 4.2.

Table 4.1: Proposed structural system classification of traditional buildings

Feature Category	Sub Category	Identifier
Siting	Building resting on the flat ground	AA
	Building resting on the flat terrain-like ground created by filling stone	BB
	Building resting on the sloping ground	CC
	Building resting on the sloping ground with a retaining wall on the downhill side	DD
	Building resting on the sloping ground with stilts	EE
	Building resting in the deep vertical cut/steep slope	FF
	Building resting in the deep vertical cut/steep slope with a retaining wall on the downhill side	GG
	Building resting in the deep vertical cut/steep slope with stilts	HH
Building Height	Up to 3 stories – Low-rise	LR
	4 and 5 stories – Mid-rise	MR
Load-bearing systems	Timber frame	TF
	Braced-timber frame with stone/brick masonry in mud mortar	TB
	Rammed earthen wall	RE
	Timber-laced stone/brick masonry	TL
	Timber frame with timber-laced stone masonry	TH
Floor System	Stone slates/stones covered with mud/earthen overlay	FL1
	Stone slates covered with a mixture of mud and cow dung	FL2
	Timber planks supported on timber/bamboo floor joists	FL3
	Timber planks supported on timber/bamboo floor joists with an earthen overlay	FL4
Roof System	Heavy-weight flat flexible roof supported on timber/bamboo floor joists	RF1
	Sloping roof with heavy-weight sheeting without cross-bracings	RF2
	Trussed roof with heavy-weight sheeting without cross-bracings	RF3
	Sloping roof with light-weight sheeting without cross-bracings	RF4
	Trussed roof with light-weight sheeting without cross-bracings	RF5
Foundation	No foundation (Thola/posts directly rest on the ground/thick stones)	FD1
	Strip footing made up of river or field stones	FD2

Light-weight sheeting: thin timber plank, Grass, Ikra, ACC, or GI sheets; Heavy-weight sheeting: thick timber plank, Stone slate.

4.7 Structural System Classification – Application Examples

Based on the developed structural system classification scheme in Section 4.6, a few examples of traditional building types with assigned structural system identifiers for based on the specific structural attributes of the building are shown in Table 4.2. The observed variations in structural attributes are summarized in Table 4.3.

Table 4.2: Typical examples of structural system classification of traditional buildings

Building Photograph	Structural Attributes	Structural System Identifier
	• On the stone platform • Three-storied • Timber-laced stone masonry • Timber planks supported on timber floor joists • Sloping roof heavy-weight sheeting without cross-bracings • Stone foundation	BB-LR-TL-FL3-RF2-FD2
	• On two foundation level • Single-storied • Timber frame with timber-laced stone masonry • Timber planks supported on timber floor joists • Sloping roof heavy-weight sheeting without cross-bracings • Stone foundation	FF-LR-TH-FL3-RF1-FD2
	• Two foundation levels • Single-storied • Rammed earthen wall • Stone covered with mud or earthen overlay • Flat flexible roof on bamboo floor joists • Stone foundation	FF-LR-RE-FL4-RF1-FD2

Table 4.3: Summary of the observed features in traditional buildings

Category/sub-category of the feature	Structural System					
	KK	TH	DD	TQ	AT	RE
Siting (Elevation shape)						
AA	✓	✓	✓	✓	✓	✓
BB	✓	×	×	×	×	
CC	×	✓	×	×	×	✓
DD	✓	✓	✓	✓	×	✓
EE	✓	✓	×	×	×	
FF	×	✓	×	×	×	✓
GG	×	✓	×	×	×	✓
HH	×	✓	×	×	✓	×
Building heights						
LR	✓	✓	✓	✓	✓	✓
MR	✓	✓	✓#	✓#	×	×
Load-bearing wall/frame systems						
KK	✓	-	-	-	-	-
TH	-	✓	-	-	-	-
DD	-	-	✓	-	-	-
TQ	-	-	-	✓	-	-
AT	-	-	-	-	✓	-
RE	-	-	-	-	-	✓
Floor systems						
FL1	✓*	✓*	✓*	✓*	✓*	✓*
FL2	×	✓*	✓*	✓*	×	×
FL3	✓	✓	✓	✓	✓	×
FL4	✓	✓	✓	✓	-	✓
Roof systems						
RF1	×	×	×	×	×	✓
RF2	✓	✓	×	×	×	×
RF3	✓	✓	×	×	×	×
RF4	✓	×	✓	✓	✓	×
RF5	✓	✓	✓	✓	✓	✓
Foundations						
FD1	×	✓	×	×	-	×
FD2	✓	✓	✓	✓	✓	✓

KK – Kath-kunni, TH – Thathara, DD – Dhajji-Dewari, TQ – Taq, AT – Assam type, RE – Rammed earth; **✓ - Observed, × - Not observed, - Not applicable,** # *Taq and Dhajji-Dewari are in combination,* * *Only seen at the ground floor level.*

CHAPTER 5

SEISMIC SAFETY MEASURES FOR TRADITIONAL BUILDINGS

5.1 General Description

The extensive field surveys and subsequent qualitative seismic vulnerability assessment conducted in Chapters 2-4 of this project form the basis for suggesting suitable seismic safety measures for further improving the earthquake resistance of traditional buildings in the study region. This Chapter includes a summary of the vulnerable features of traditional buildings (Table 5.1) and the seismic safety measures for both the existing as well as new traditional buildings. The sketches developed in this Chapter are collected from the various codes of practice (BIS 1993c; SAZS 2001; IS13827 1993; IS13828 1993; IS14243-2 1995; IS4326 1993) and existing literature (Ibáñez et al. 2012; Vargas-Neumann et al. 2007; Dowling et al. 2005; Reyes et al. 2019a, b, Schacher and Ali 2009). A ready to use guidance sketches have been prepared, including the various siting, architectural, structural, and foundation features that can be used to construct traditional buildings. This chapter discusses in detail the siting features such as siting locations that have to be avoided or preferred, various architectural features including the selection of the plan shape, elevation, horizontal projections, the orientation of walls and wall length, placement of the openings, length of openings, and story heights. All the recommended aspects are the general minimum requirements that need to be followed during the construction of new traditional buildings.

Out of all the structural systems discussed in this report, rammed earth buildings have been found to be the most vulnerable. Hence, the step-by-step procedure to enhance the earthquake resistance of single-story rammed earthen buildings (existing and new) has also been presented. It shall be noted that these provisions are to be applied to build earthquake-resistant single-story rammed earthen buildings with attic space. These provisions do not allow bypassing the requirements of existing Indian standards on improving earthquake resistance of earthen buildings. In addition, to improve the earthquake resistance of existing traditional buildings, provisions to improve floor rigidity, roof rigidity, and provisions to improve the connections between members of timber frames and roof truss are also presented in sketches. The provisions given in this chapter can aid in reducing the commonly observed deficiencies during the construction of traditional houses. It shall be noted that when the observed features are either earthquake-resilient, for these specific features no measures are suggested in this study. The traditional methods for improving earthquake resilience of traditional buildings are shown in Figs. 5.9-5.27 and the advanced (modern) methods for improving earthquake resilience of traditional buildings are shown in Figs. 5.28-5.30.

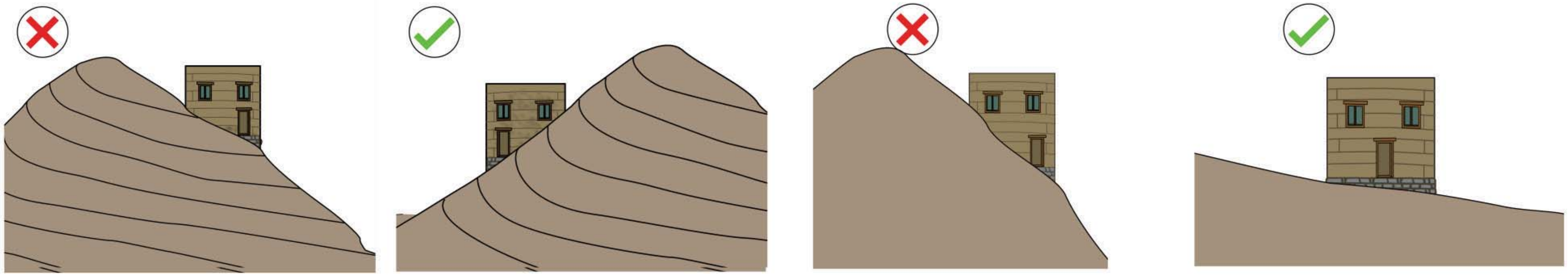
Table 5.1: Summary of earthquake-resilient and vulnerable features in traditional buildings

S. No.	Features	Earthquake-resilient and vulnerable features						Suggested safety measures
		KK	TH	DD	TQ	AS	RE	
1.	**Siting features**							
(a)	Flat ground	🟩	🟩	🟩	🟩	🟩	🟩	No specific measures suggested
(b)	Sloping ground	-	🟥	-	-	-	🟥	Refer to Figures 5.1 and 5.2
(c)	Hill top	-	-	-	-	-	🟥	Refer to Figures 5.1 and 5.2
2.	**Architectural features**							
(a)	Plan shape	🟩	🟨	🟨	🟨	🟨	🟨	Refer to Figure 5.3
(b)	Elevation	🟩	🟩	🟩	🟩	🟩	🟨	Refer to Figure 5.4
(c)	Small horizontal projections	🟩	🟩	🟨	🟨	🟩	🟩	Refer to Figure 5.4
(d)	Wall length	🟩	🟩	-	-	-	🟨	Refer to Figures 5.5 and 5.8
(e)	Symmetry of wall/frame	🟩	🟩	🟩	🟩	🟩	🟨	Refer to Figure 5.5
(f)	Placement of openings	🟩	🟩	🟩	🟩	🟩	🟨	Refer to Figure 5.6
(g)	Number of openings	🟩	🟨	🟩	🟥	🟩	🟨	Refer to Figure 5.6
(h)	Uniformity of story height	🟩	🟩	🟩	🟩	🟩	🟩	Refer to Figure 5.4
(i)	Number of stories	🟩	🟩	🟩	🟩	🟩	🟨	-
(j)	Gap between buildings	🟨	🟨	🟨	🟨	🟨	🟨	-
3.	**Structural features**							
(a)	Gravity/Lateral load path	🟩	🟩	🟩	🟩	🟩	🟩	No specific measures suggested
(b)	Wall density	🟩	🟩	-	-	-	🟩	No specific measures suggested
(c)	Redundancy	🟩	🟩	🟩	🟩	🟩	🟩	No specific measures suggested
(d)	Roof weight	🟥	🟥	🟩	🟩	🟩	🟥	-
(e)	Roof-to-wall/frame connection	🟩	🟥	🟩	🟩	🟩	🟥	Refer to Figures 5.14-5.20
(f)	Wall/Frame-to-foundation connection	🟥	🟥	🟩	🟥	🟩	🟥	Refer to Figure 5.7
(g)	Wall-to-wall connection	🟩	🟩	-	🟩	-	🟥	Refer to Figures 5.9-5.13, 5.21-23, 5.26, 5.28-5.29
(h)	Roof connections	🟩	🟩	🟩	🟩	🟩	-	Refer to Figure 5.27
(i)	Floor-to-wall connections	🟩	🟩	🟩	-	-	🟥	Refer to Figure 5.14
(j)	Roof rigidity	🟥	🟥	🟥	🟥	🟥	🟥	Refer to Figure 5.25
(k)	Floor rigidity	🟥	🟥	🟥	🟥	-	🟥	Refer to Figures 5.24 and 5.30
4.	**Soil conditions and foundations**							
(a)	Soil condition	🟨	🟨	🟨	🟨	🟨	🟨	Refer to Figure 5.1
(b)	Provision of plinth band	🟩	🟩	-	🟩	-	🟥	Refer to Figure 5.7
(c)	Foundation size	🟩	🟩	🟩	🟩	🟩	🟩	Refer to Figure 5.7
5.	**Visual conditions and maintenance**							
(a)	Visual condition	🟨	🟨	🟨	🟨	🟨	🟨	No specific measures suggested
(b)	Maintenance	🟨	🟨	🟨	🟨	🟨	🟨	No specific measures suggested
(c)	Material deterioration	🟨	🟨	🟨	🟨	🟨	🟨	No specific measures suggested
6.	**Other features**							
(a)	Seismic weight	🟥	🟥	🟩	🟥	🟩	🟥	No specific measures suggested
(b)	Damping	🟩	🟩	🟩	🟩	🟩	🟥	No specific measures suggested
(c)	Deformability	🟩	🟩	🟩	🟩	🟩	🟥	No specific measures suggested

🟩	Earthquake-resilient	🟨	Earthquake resilient/vulnerable	🟥	Earthquake-vulnerable	-	Not applicable

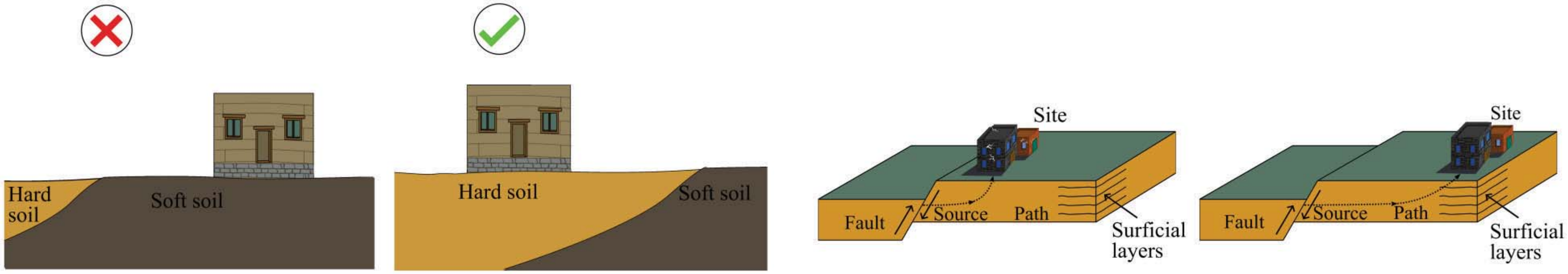
5.2 GENERAL SEISMIC SAFETY MEASURES

SITE SELECTION FOR BUILDING CONSTRUCTION: DO'S AND DON'T'S



Avoid downhill side of the bedding plane

Avoid slopes greater than 45 degree

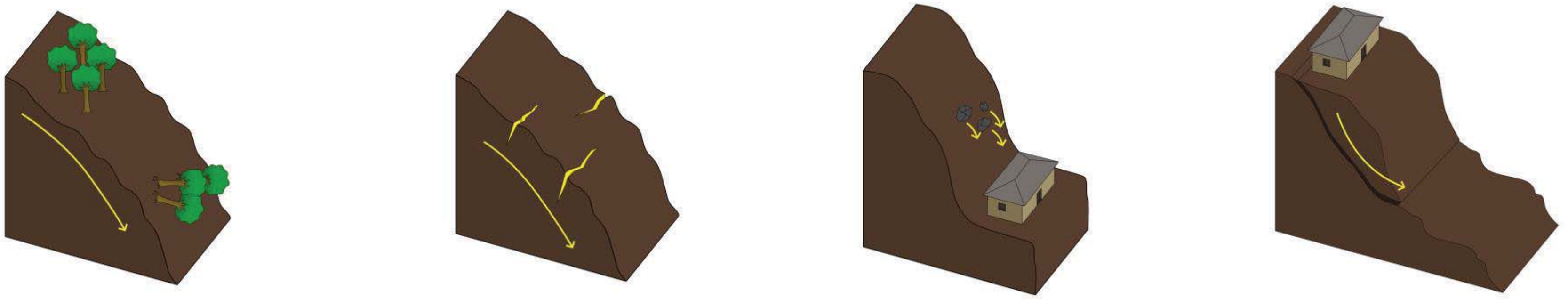


Avoid soft soil

Avoid construction near active faults

Figure 5.1: Selection of site for construction of new buildings. The recommendation applies to all traditional buildings

SITE SELECTION: SITES TO BE AVOIDED

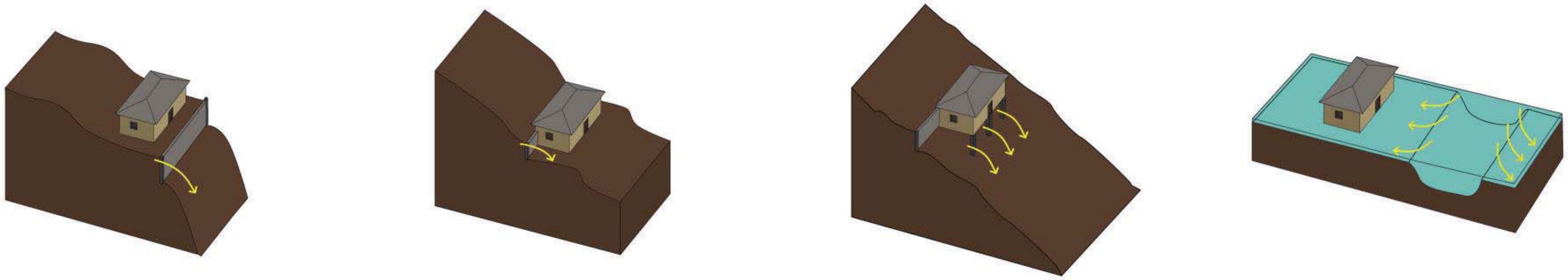


Avoid site where trees bend downward

Avoid terrain with cracks

Avoid bottom of steep slope

Avoid construction on steep cliff



Avoid construction near poorly constructed retaining wall

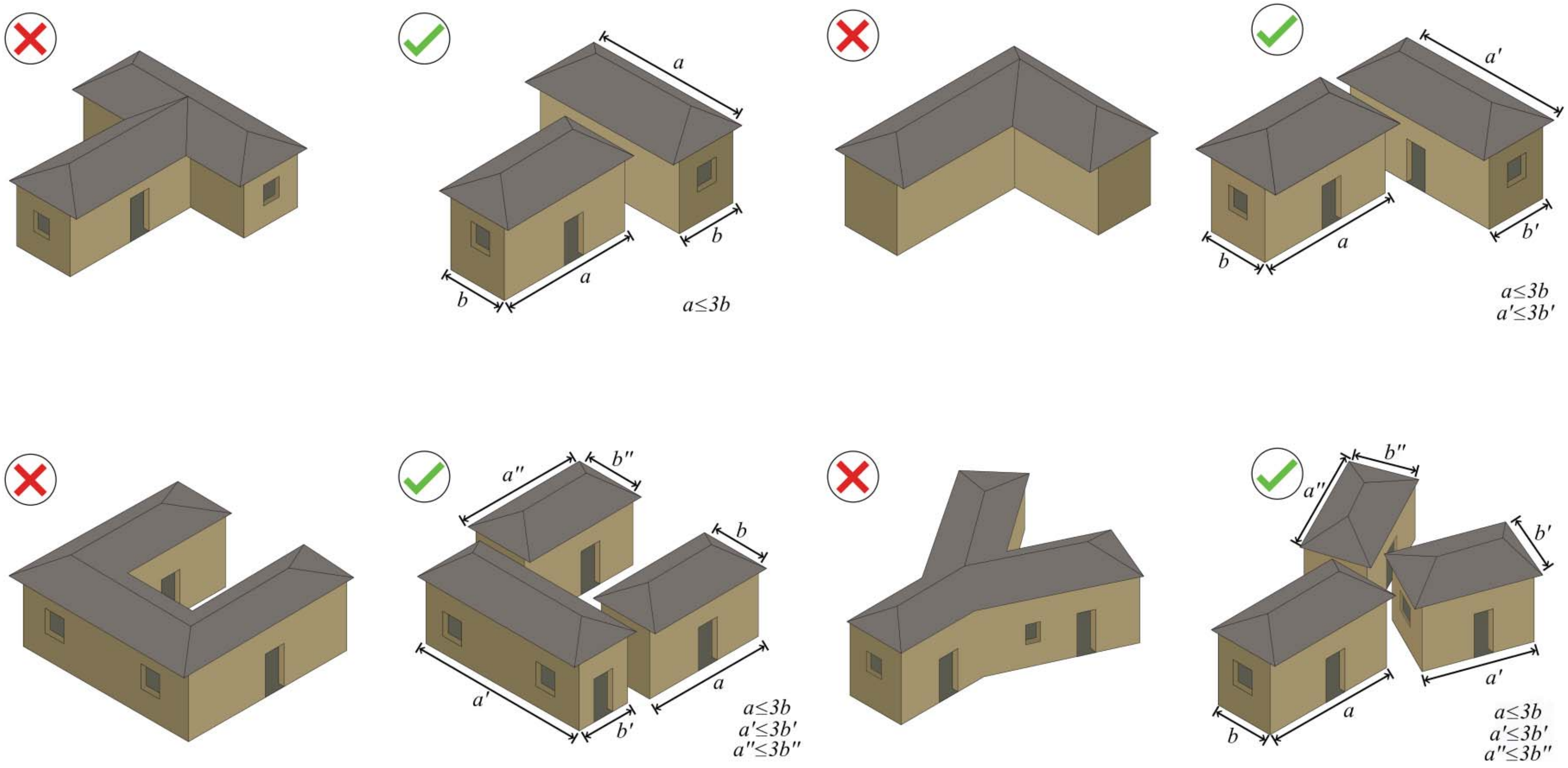
Avoid construction adjacenet to poorly constructed retaining wall

Avoid construction on free-standing posts

Avoid construction near water bodies

Figure 5.2: Sites to be avoided for construction of new traditional buildings. The recommendation applies to all traditional buildings

BUILDING PLAN SHAPE

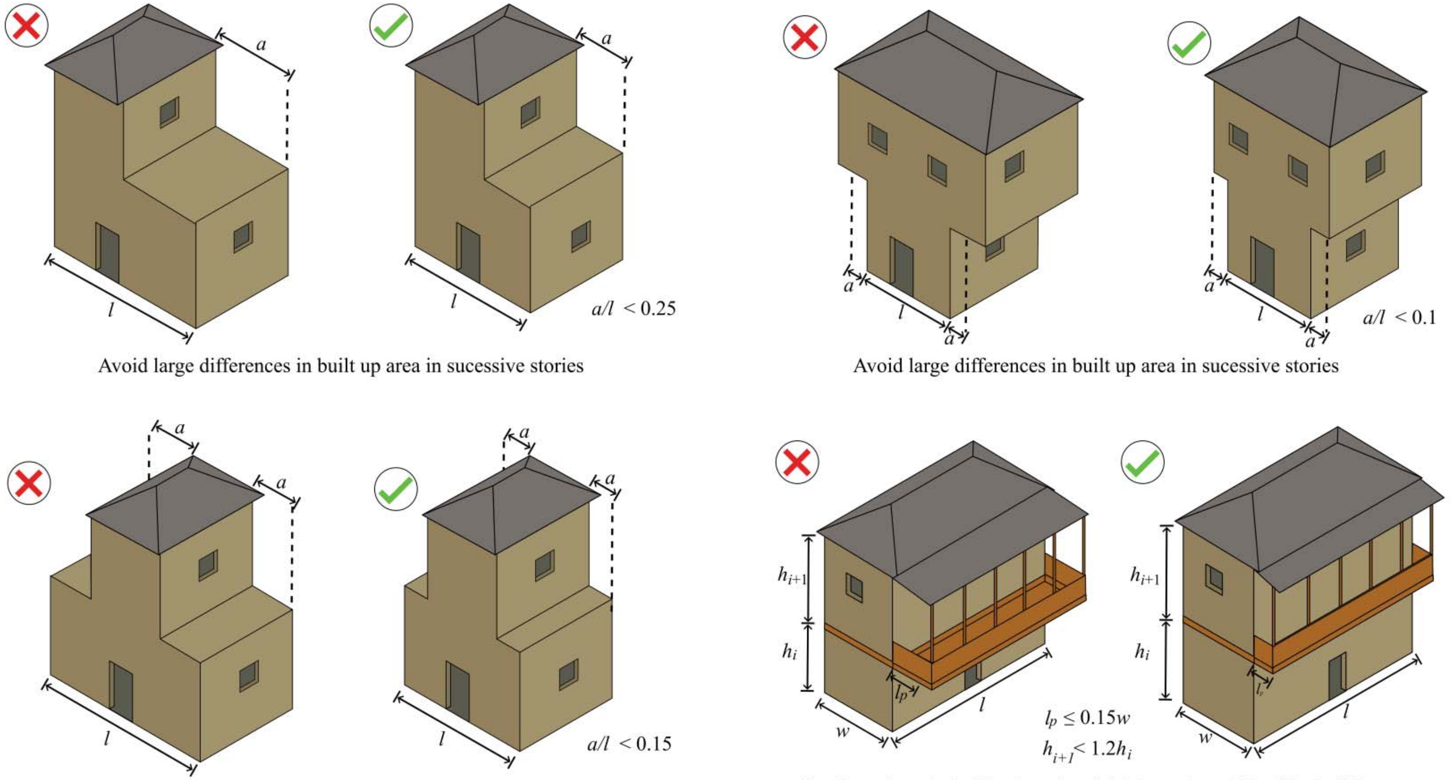


Do not select complex plan shape, divide plan into simple rectangular shapes.

$a/a'/a''$ = length of the building, $b/b'/b''$ = width of the building

Figure 5.3: Selection of building plan shape for new traditional buildings. The recommendation applies to all traditional buildings

BUILDING ELEVATION SHAPE AND HORIZONTAL PROJECTIONS



Avoid large differences in built up area in sucessive stories

Avoid large differences in built up area in sucessive stories

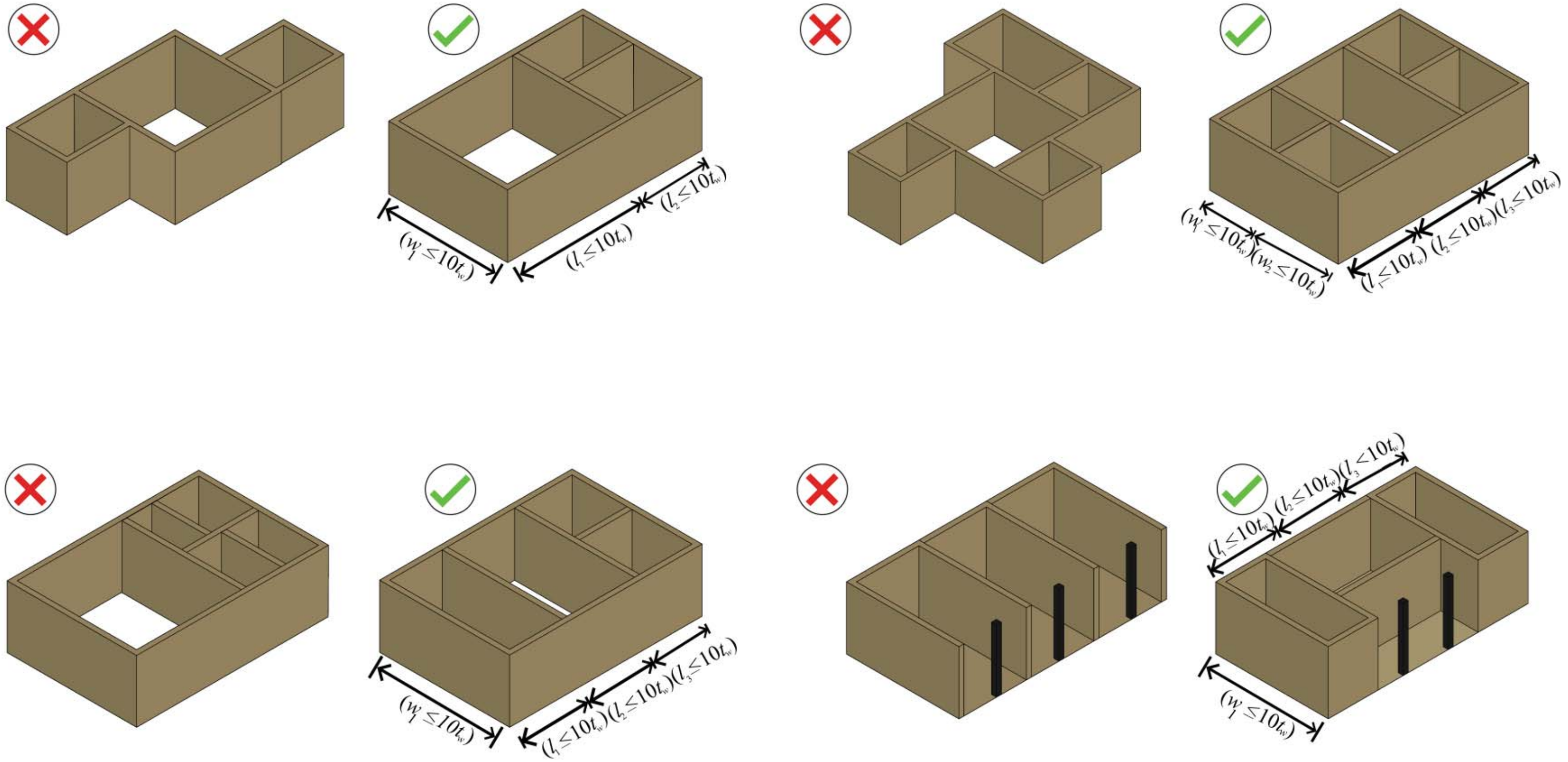
Avoid large differences in built up area in sucessive stories

a/l = setback ratio, l_p = length of projection, w = width of building, l = length of building
h_i = height of i^{th} story, h_{i+1} = height of $i+1^{th}$story

Overhang length shall be less than 0.15 times the width of the building in the direction of the overhang. Avoid large differences in the height of two successive stories

Figure 5.4: Selection of building elevation shape and horizontal projections for new traditional buildings. The recommendation applies to all traditional buildings

PLACEMENT OF WALLS



Avoid un-symmetrical placement of walls and too many verandas

t_w= thickness of wall, $l_1/l_2/l_3$= wall length along the length of building between cross-walls, $w_1/w_2/w_3$= wall length along the width of building between cross-walls

Figure 5.5: Placement of walls for new traditional buildings. The recommendation applies to all traditional buildings

PLACEMENT OF OPENINGS

Avoid too many windows/doors

Avoid large windows/doors

Avoid placing all openinngs in the same wall

Prefer openings few in numbers and smaller in size

Avoid placing openings nearer to corners

Place openings atleast 0.6*m* from corners

Avoid deep verandas

Prefer verandas not greater than 1/3rd of the length of building

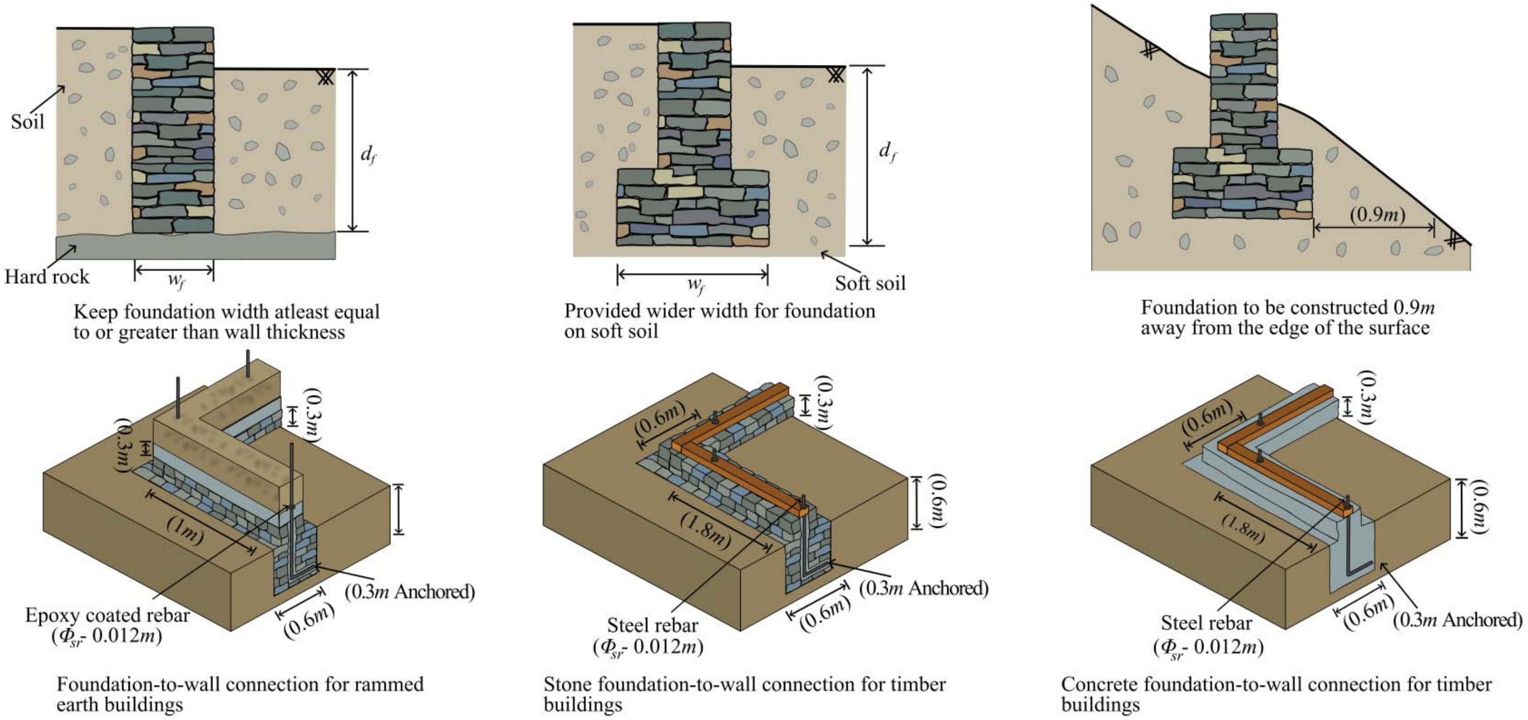
Note: The sum of length of openings should not exceed 33% of length of the wall in either of the horizontal directions.

$a/b/c$ = width of door/window opening, l = length of wall, l' = length of veranda

$$\frac{a+b+c}{l} \leq 0.33$$

Figure 5.6: Placement of openings in walls for new traditional buildings. The recommendation applies to all traditional buildings

FOUNDATION SIZES AND FOUNDATION-TO-WALL-CONNECTIONS



Keep foundation width atleast equal to or greater than wall thickness

Provided wider width for foundation on soft soil

Foundation to be constructed 0.9m away from the edge of the surface

Foundation-to-wall connection for rammed earth buildings

Stone foundation-to-wall connection for timber buildings

Concrete foundation-to-wall connection for timber buildings

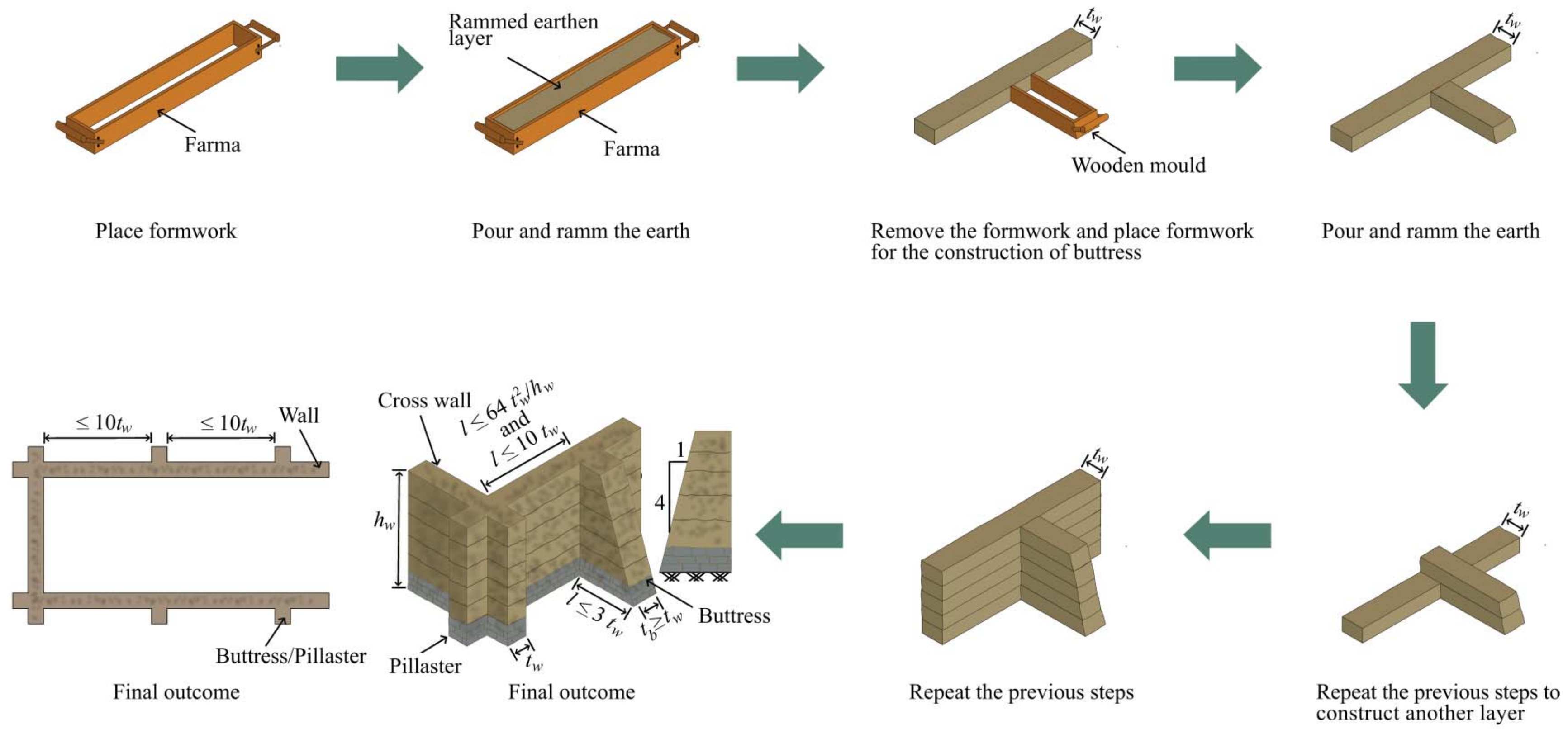
Minimum foundation size

Building typology	Hard soil		Soft soil	
	w_f	d_f	w_f	d_f
Rammed earth	t_w	0.4m	1.5t_w	0.6m
Other typologies	max(t_w,0.45m)	0.6m	max(t_w,0.6m)	1.5m

d_f = depth of foundation, w_f = width of foundation, t_w = thickness of wall
Φ_{sr} = diameter of steel rebar

Figure 5.7: Foundation sizes and foundation-to-wall/frame connections for new traditional buildings. The recommendation applies to all traditional buildings

PROVISION OF BUTTRESS WALL

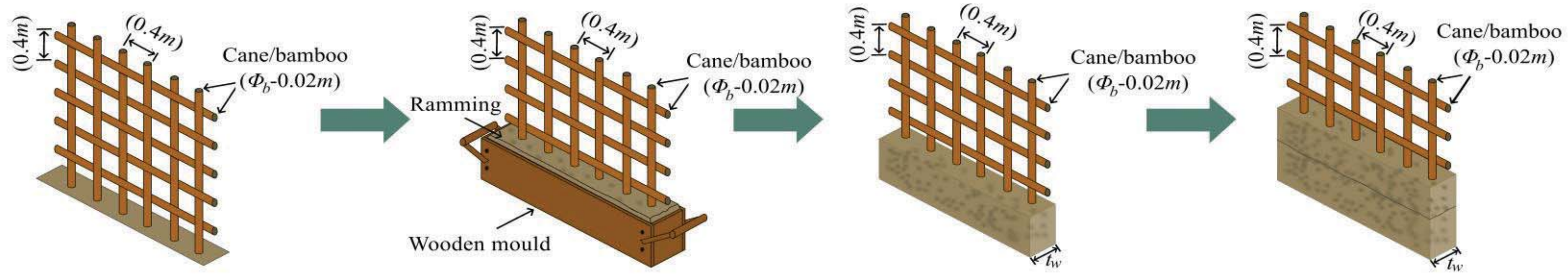


t_w = thickness of wall, l = length of wall, t_b = thickness of buttress, h_w = height of wall

Figure 5.8: Provisions of buttress wall for new rammed earth buildings

5.3 TRADITIONAL METHODS FOR IMRPOVING EARTHQUAKE RESISTANCE OF TRADITIONAL BUILDINGS

BAMBOO REINFORCEMENT IN WALLS



Place bamboo reinforcement having a spacing of 0.4*m* both horizontally and vertically

Pour and ramm the earth in formwork

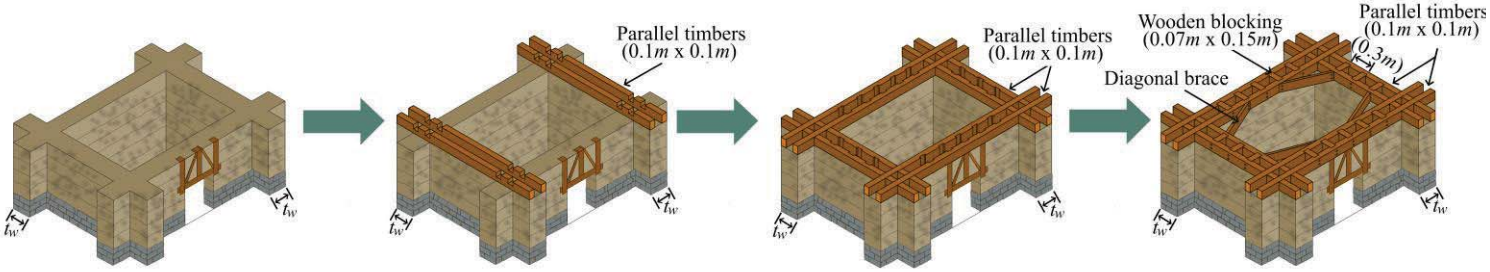
Remove the formwork

Repeat the steps to construct the wall

t_w = thickness of wall, Φ_b = diameter of bamboo

Figure 5.9: Provisions of bamboo reinforcement for new rammed earth buildings

PROVISION OF SEISMIC BANDS



Structure prior to seismic band connection

Placement of seismic bands

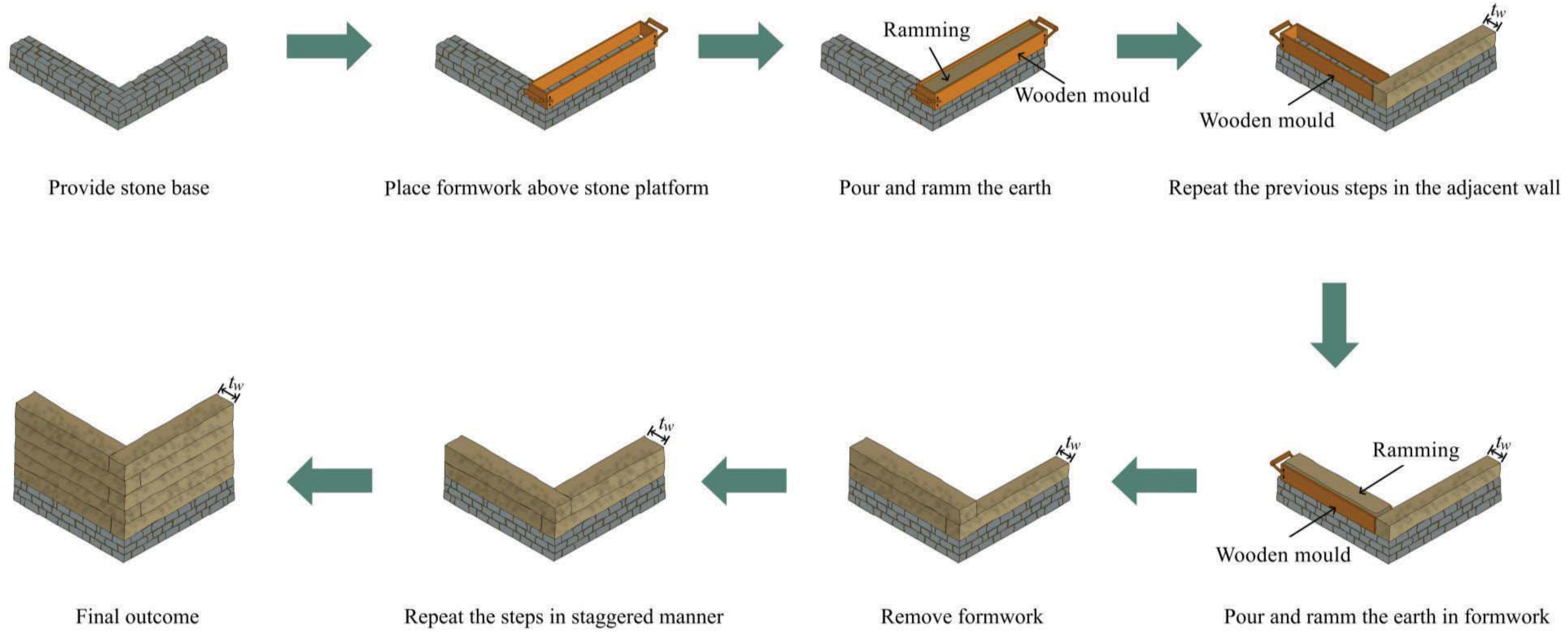
Place seismic bands in the opposite direction along with vertical grooves

Place horizontal and diagonal memebers and nail them for firm connection of bands

t_w = thickness of wall

Figure 5.10: Provisions of seismic bands in new rammed earth buildings

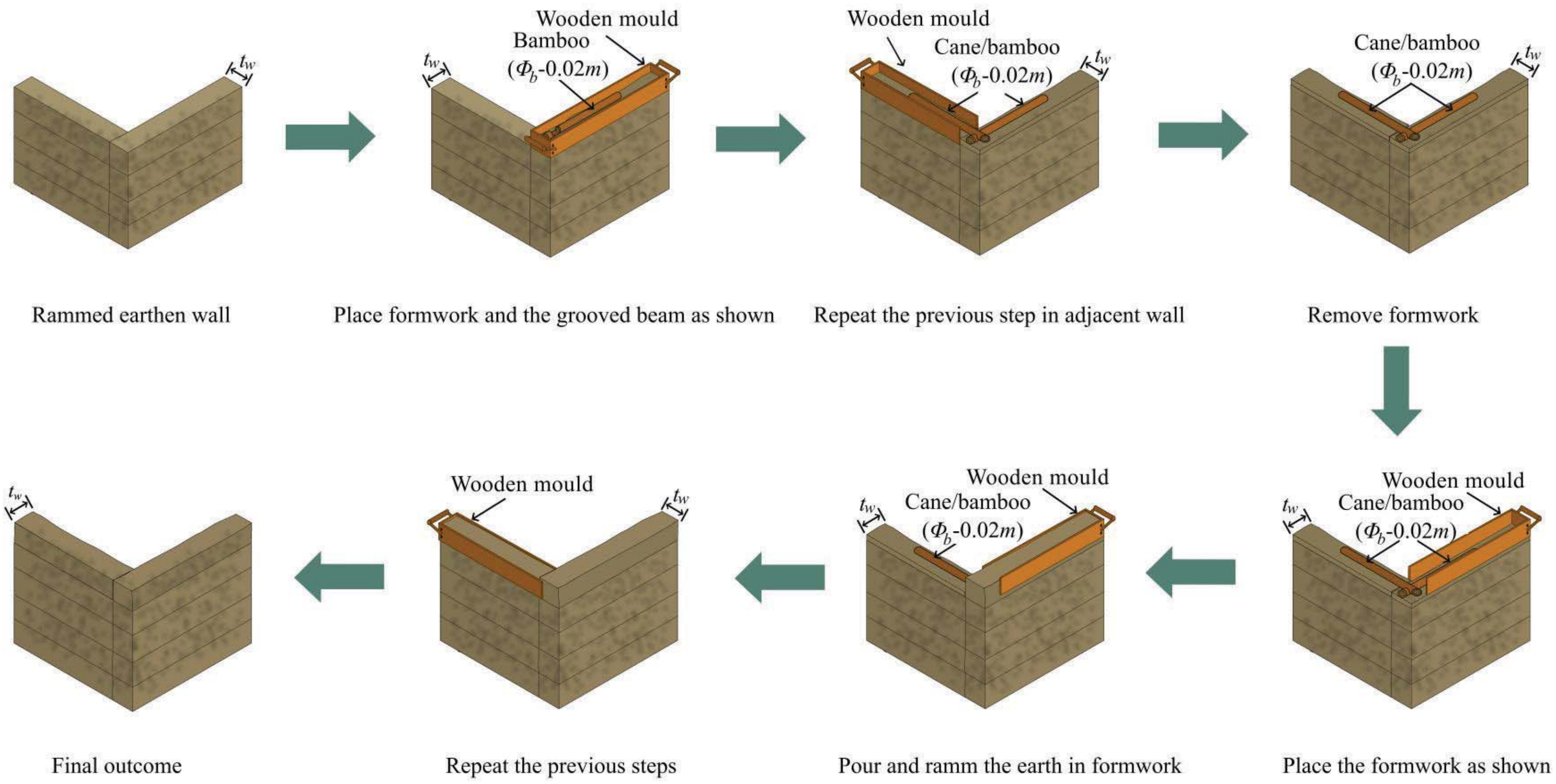
STAGGERING OF WALL-TO-WALL JOINTS



t_w = thickness of wall

Figure 5.11: Provisions of staggering wall-to-wall joints for new rammed earth buildings

PLACEMENT OF BAMBOO FOR WALL-TO-WALL CONNECTIONS

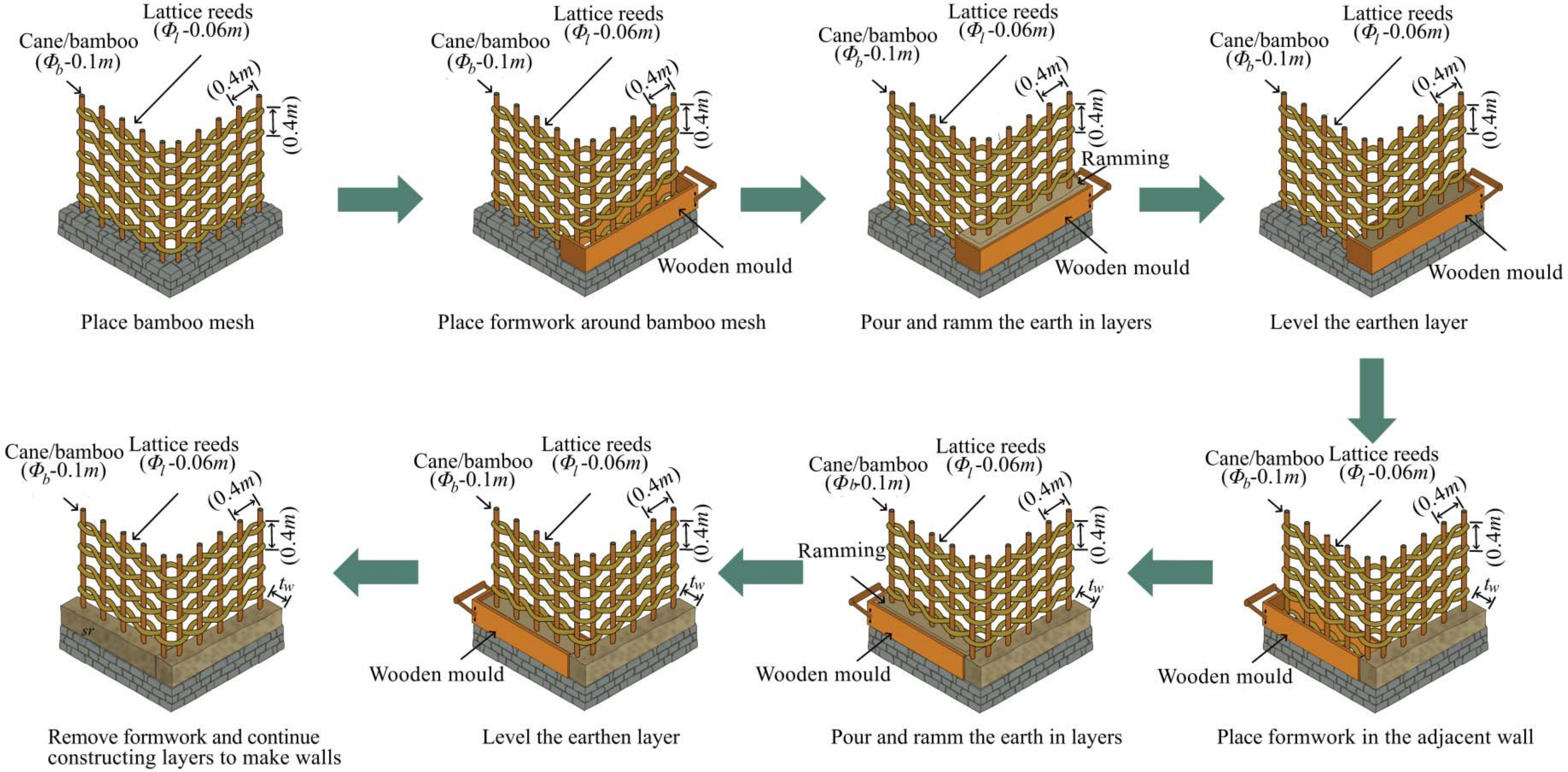


Note:The above steps shall be repeated at every 0.3m along the height of the wall.

t_w= thickness of wall, Φ_b = diameter of bamboo

Figure 5.12: Provisions of bamboo for wall-to-wall connections in new rammed earth buildings

BAMBOO REINFORCEMENT FOR WALL-TO-WALL CONNECTIONS

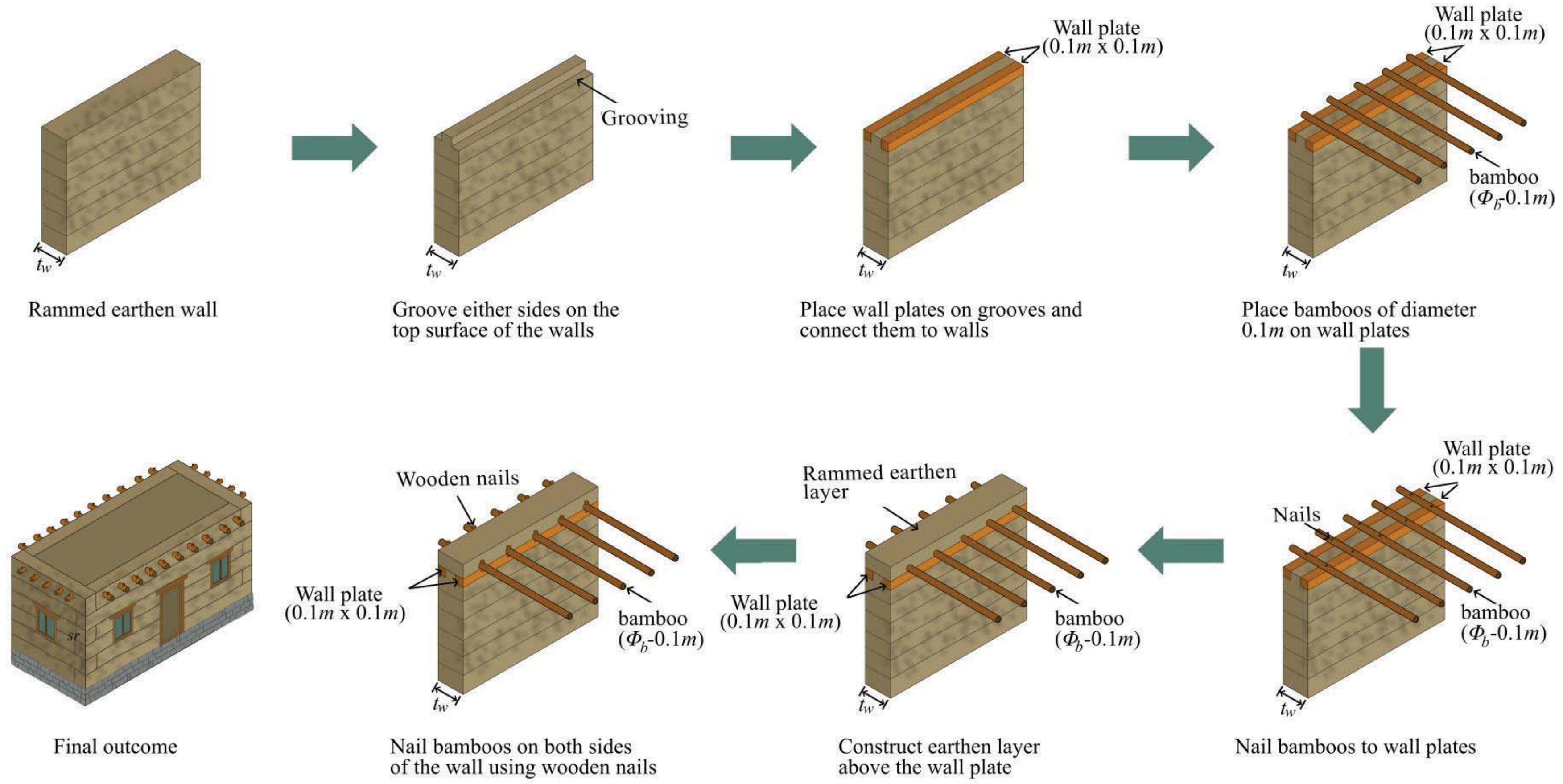


Note: The bamboo mesh is created by using bamboos of diameter 0.1m for vertical memebers that are placed at a distance of 0.4m uniformally and the bamboos are connected by lattice reeds uniformally at a spacing of 0.4m.

t_w= thickness of wall, Φ_b = diameter of bamboo, Φ_l = diameter of lattice reeds

Figure 5.13: Provisions of bamboo connected by lattice reeds for wall-to-wall connections in new rammed earth buildings

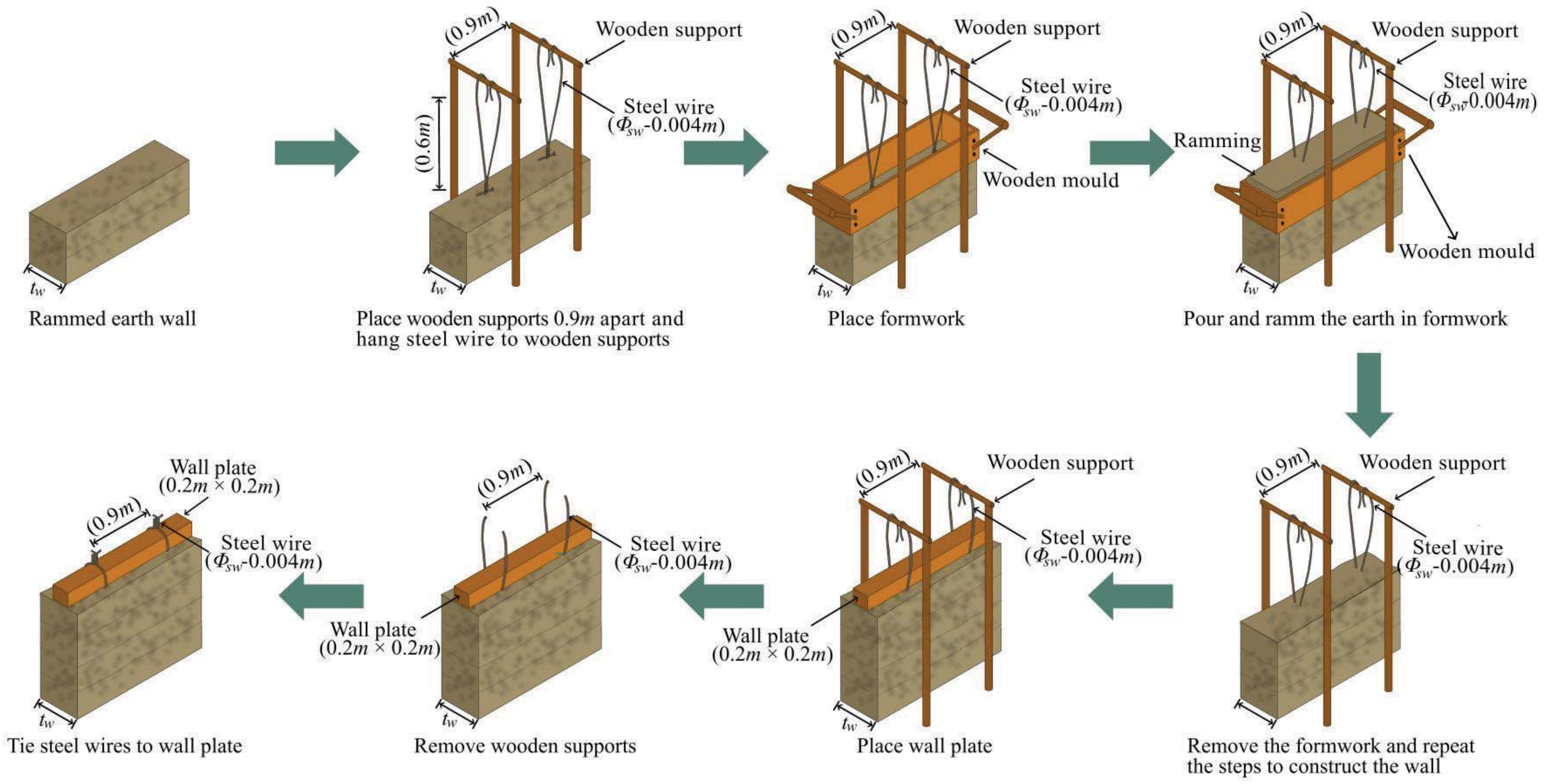
FLOOR/ROOF-TO-WALL CONNECTIONS



t_w = thickness of wall, Φ_b = diameter of bamboo

Figure 5.14: Floor/roof-to-wall connections in new rammed earth buildings

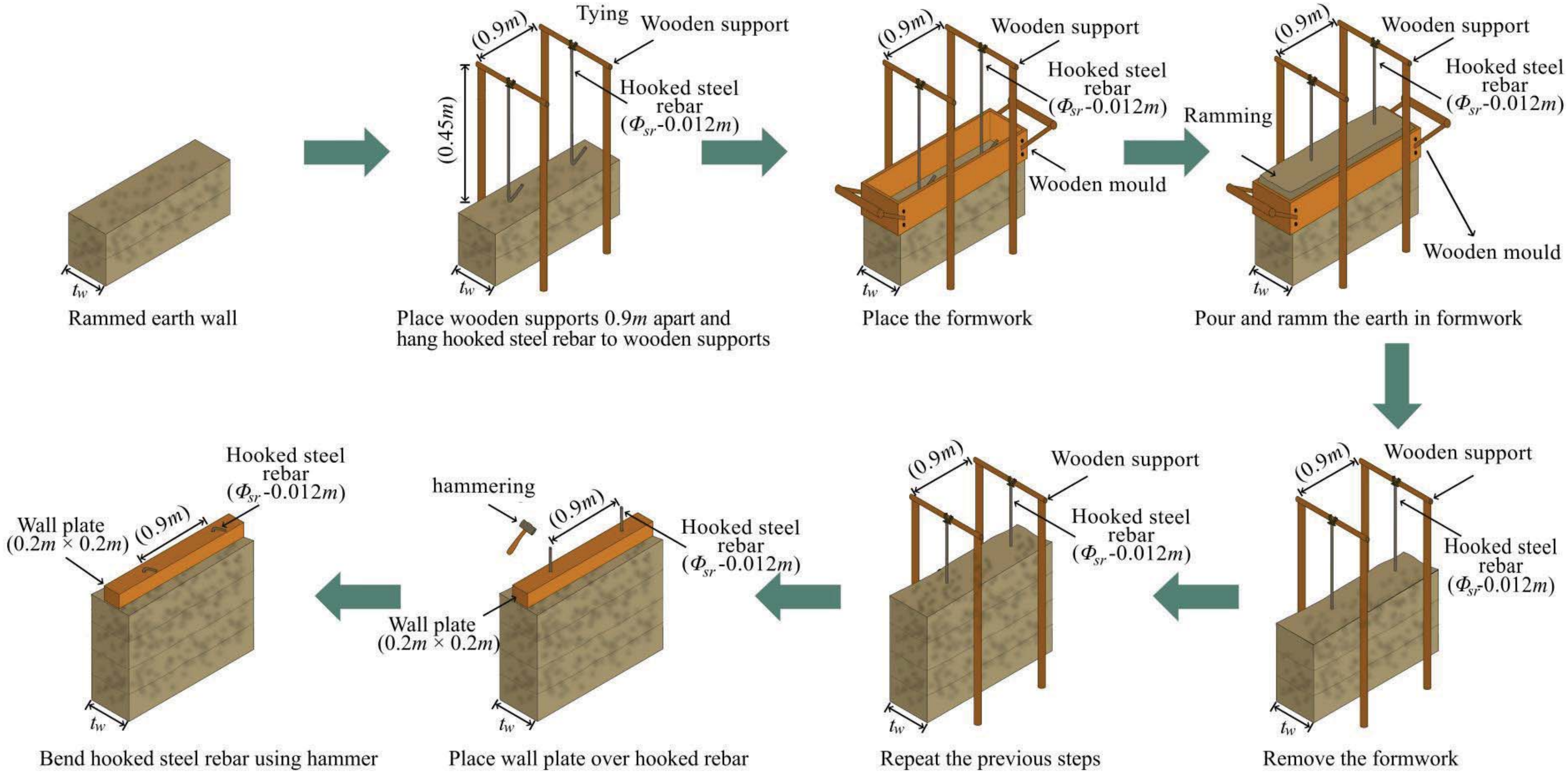
WALL PLATE-TO-WALL CONNECTIONS



t_w= thickness of wall, Φ_{sw}= diameter of steel wire

Figure 5.15: Wall plate-to-wall connections in new rammed earth buildings

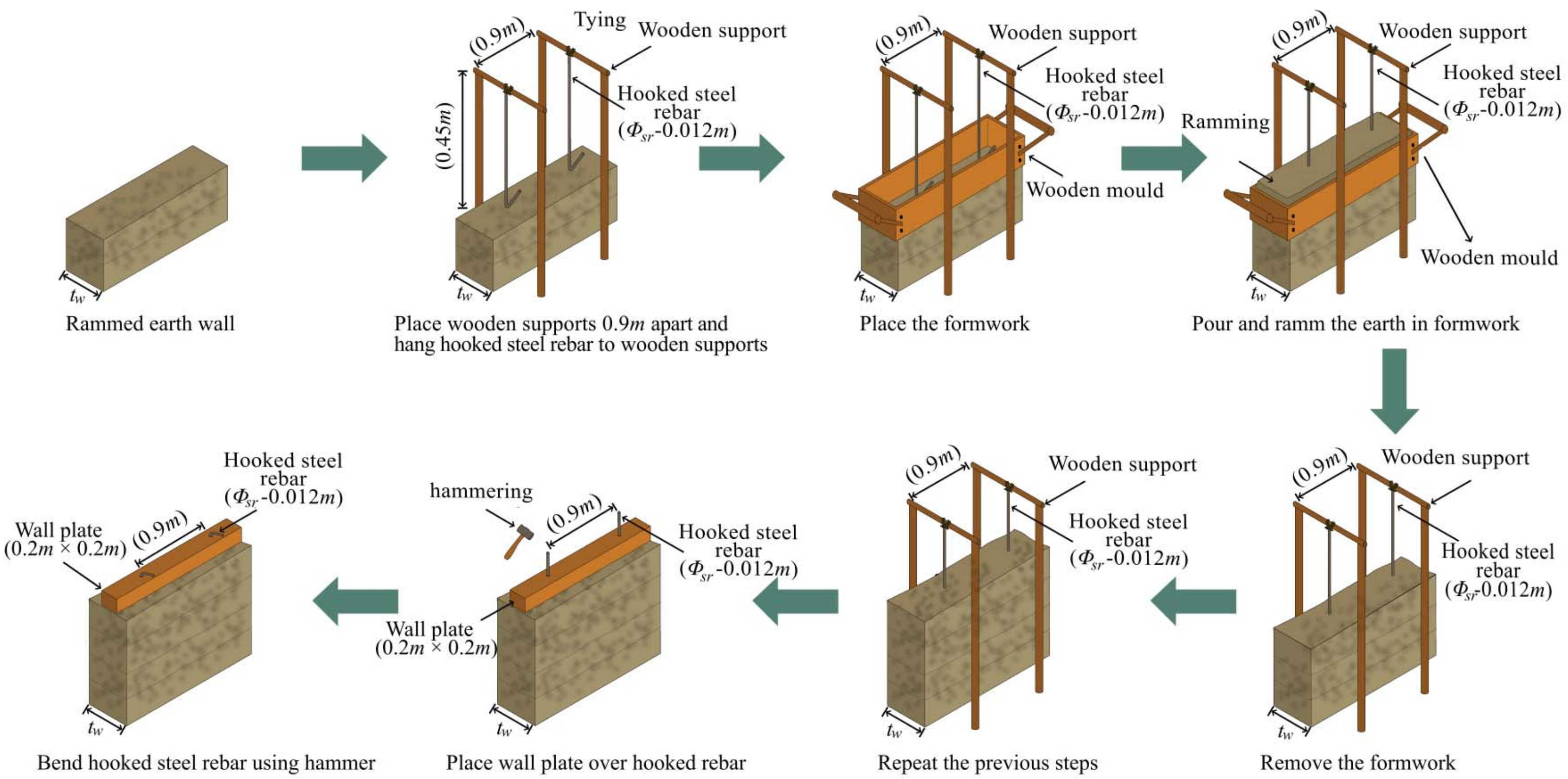
WALL PLATE-TO-WALL CONNECTIONS



t_w= thickness of wall, Φ_{sr}= diameter of steel rebar

Figure 5.16: Wall plate-to-wall connections in new rammed earth buildings

WALL PLATE-TO-WALL CONNECTIONS



Rammed earth wall

Place wooden supports 0.9m apart and hang hooked steel rebar to wooden supports

Place the formwork

Pour and ramm the earth in formwork

Remove the formwork

Repeat the previous steps

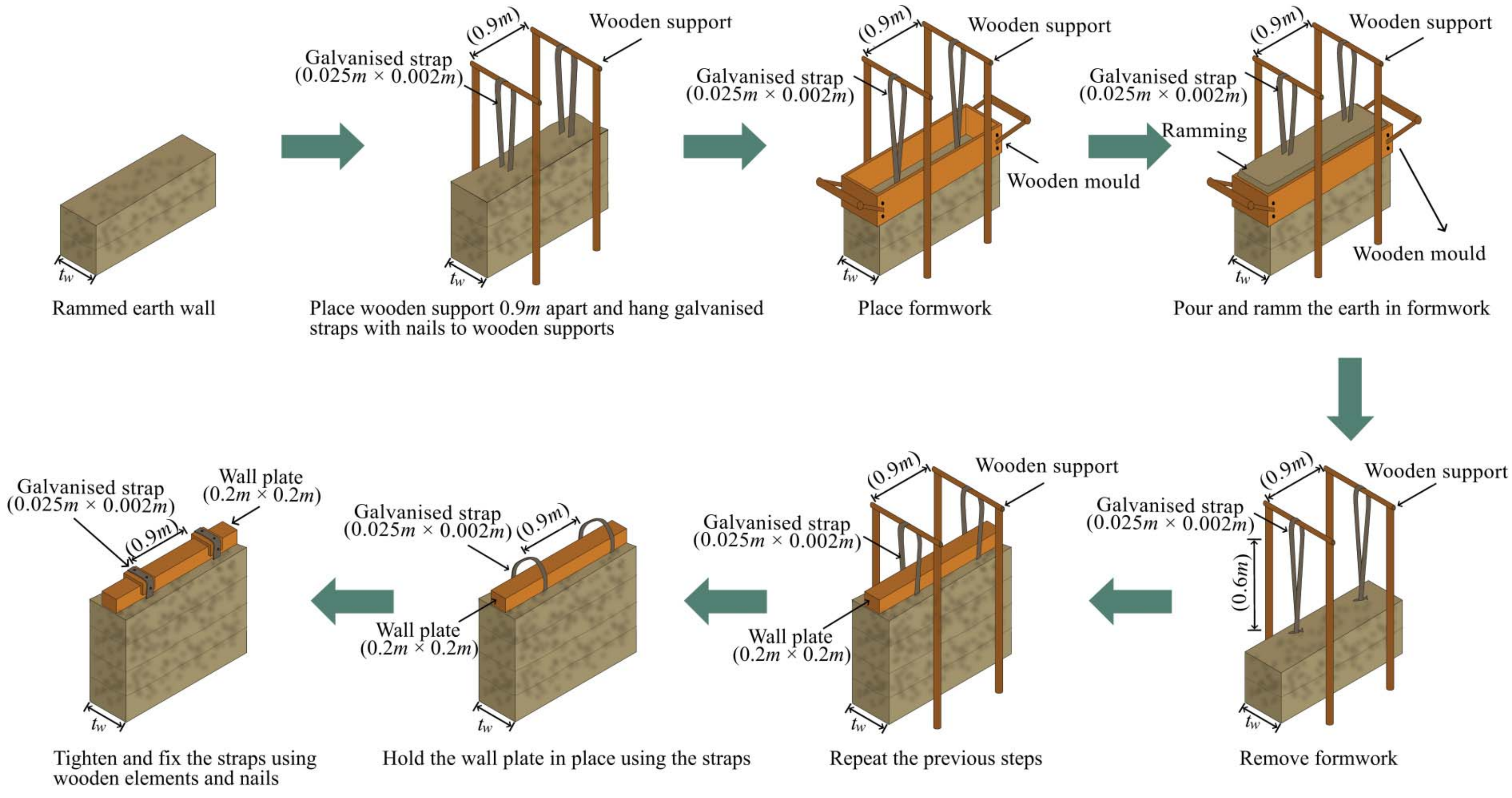
Place wall plate over hooked rebar

Bend hooked steel rebar using hammer

t_w= thickness of wall, Φ_{sr} = diameter of steel rebar

Figure 5.17: Wall plate-to-wall connections in new rammed earth buildings

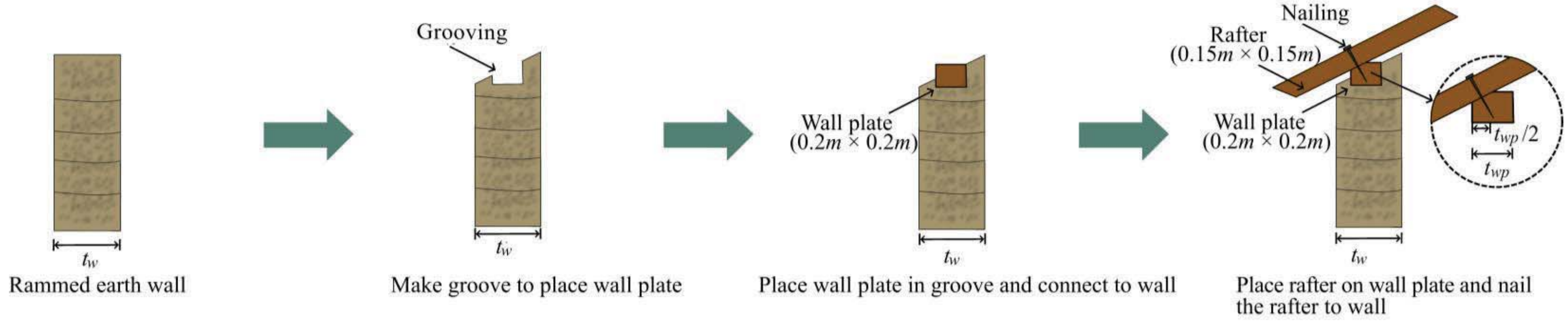
WALL PLATE-TO-WALL CONNECTIONS



t_w= thickness of wall

Figure 5.18: Wall plate-to-wall connections in new rammed earth buildings

RAFTER-TO-WALL PLATE CONNECTIONS

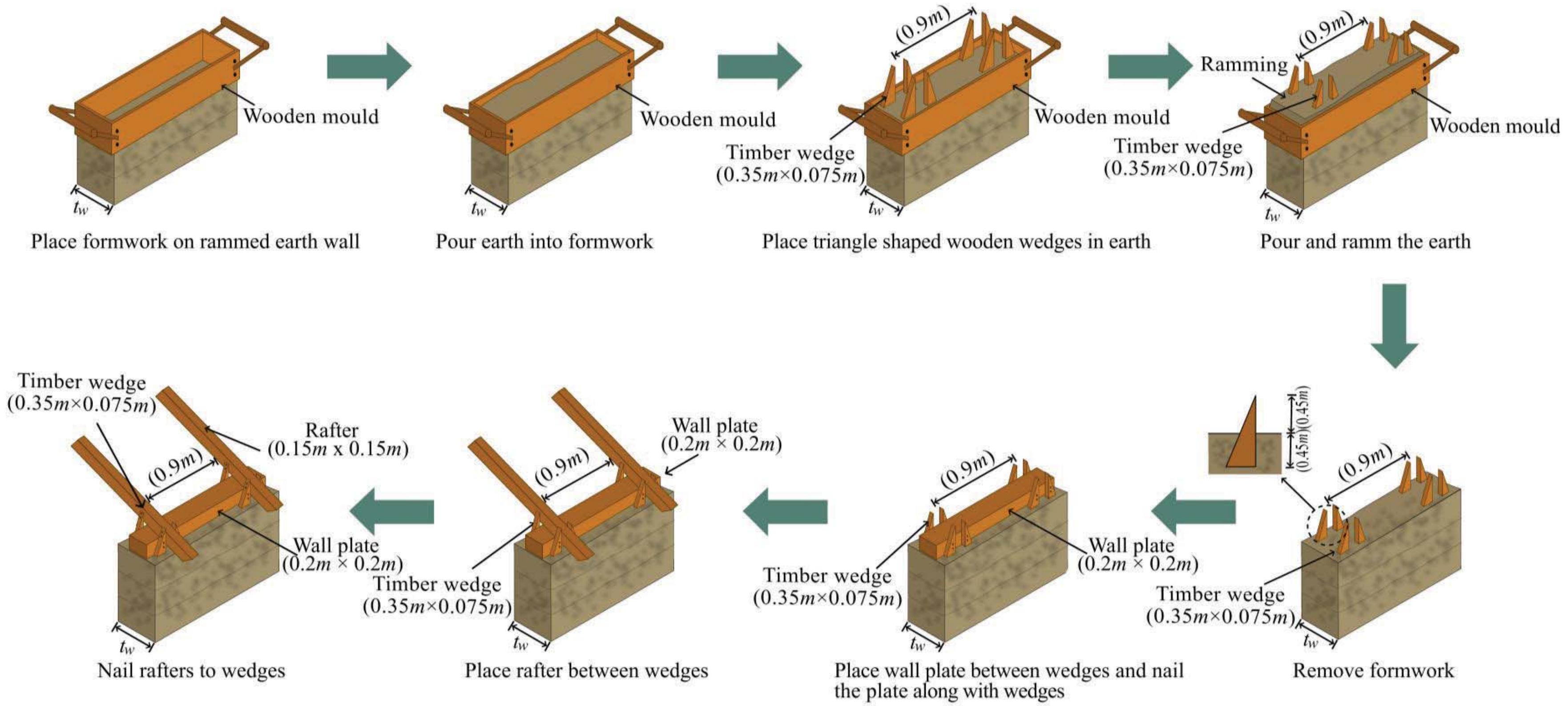


Note: Wall plate shall be connected with wall with the appropriate measure as suggested in the document.

t_w= thickness of wall, t_{wp} = thickness of wall plate

Figure 5.19: Rafter-to-wall plate connections in new rammed earth buildings

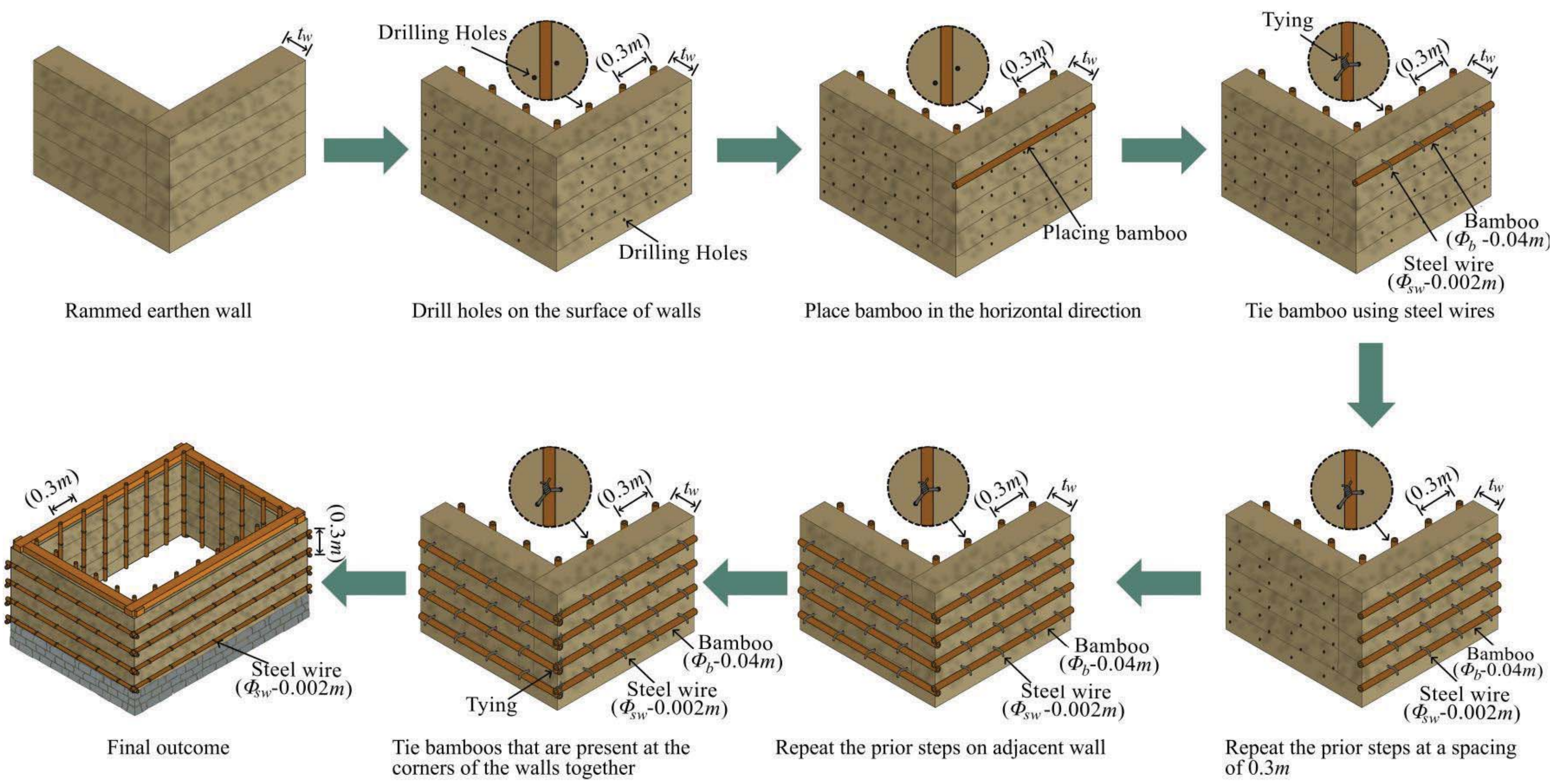
RAFTER-TO-WALL PLATE CONNECTIONS



t_w= thickness of wall

Figure 5.20: Rafter-to-wall plate connections in new rammed earth buildings

EXTERNAL HORIZONTAL BAMBOO REINFORCEMENT



Rammed earthen wall

Drill holes on the surface of walls

Place bamboo in the horizontal direction

Tie bamboo using steel wires

Repeat the prior steps at a spacing of 0.3m

Repeat the prior steps on adjacent wall

Tie bamboos that are present at the corners of the walls together

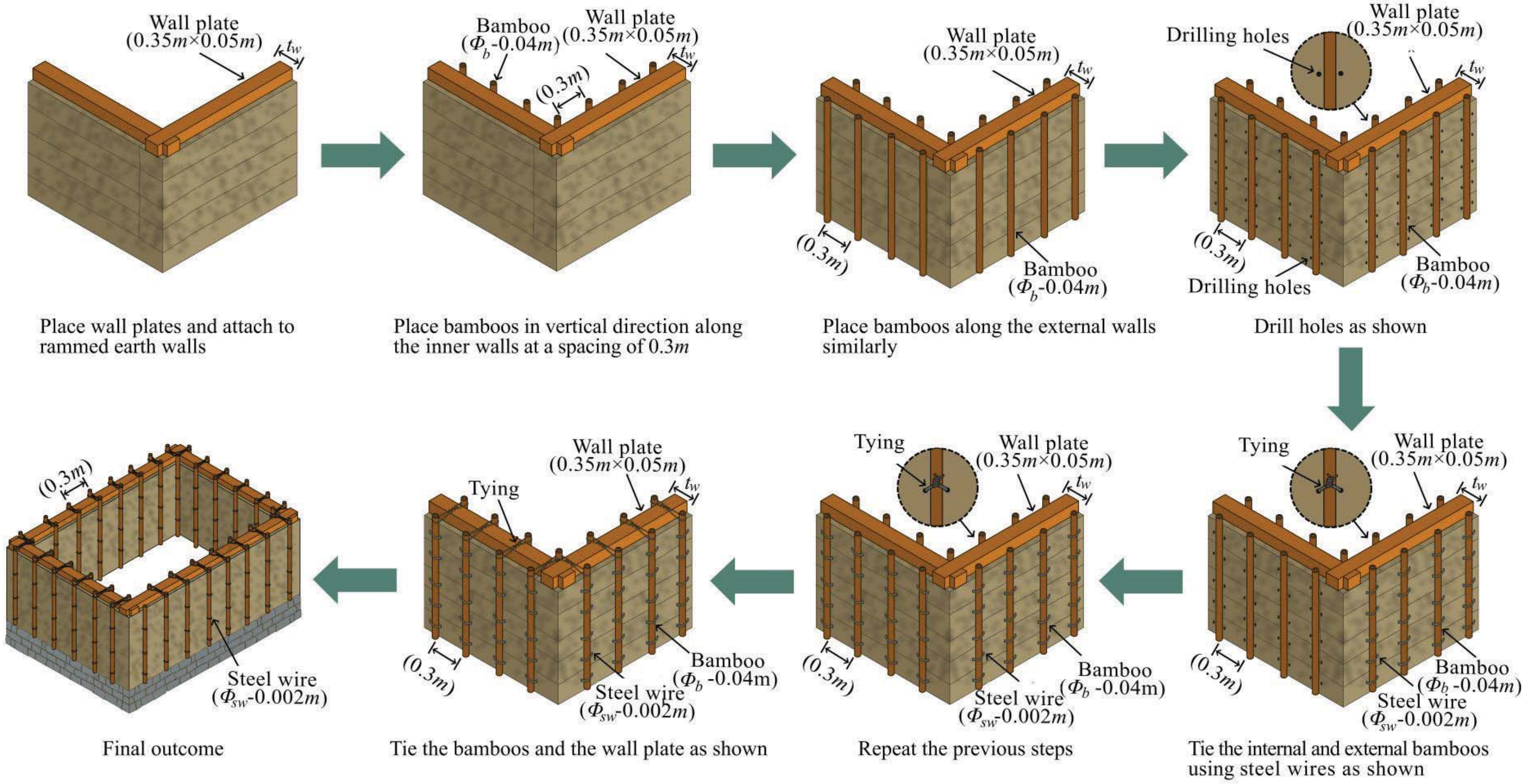
Final outcome

Note: Vertical bamboos are provided on the inner wall faces at a spacing of 0.3m.

t_w= thickness of wall, Φ_{sw}= diameter of steel wire, Φ_b = diameter of bamboo

Figure 5.21: Strengthening existing rammed earth buildings using bamboo externally horizontally

EXTERNAL VERTICAL BAMBOO REINFORCEMENT



Place wall plates and attach to rammed earth walls

Place bamboos in vertical direction along the inner walls at a spacing of 0.3m

Place bamboos along the external walls similarly

Drill holes as shown

Tie the internal and external bamboos using steel wires as shown

Repeat the previous steps

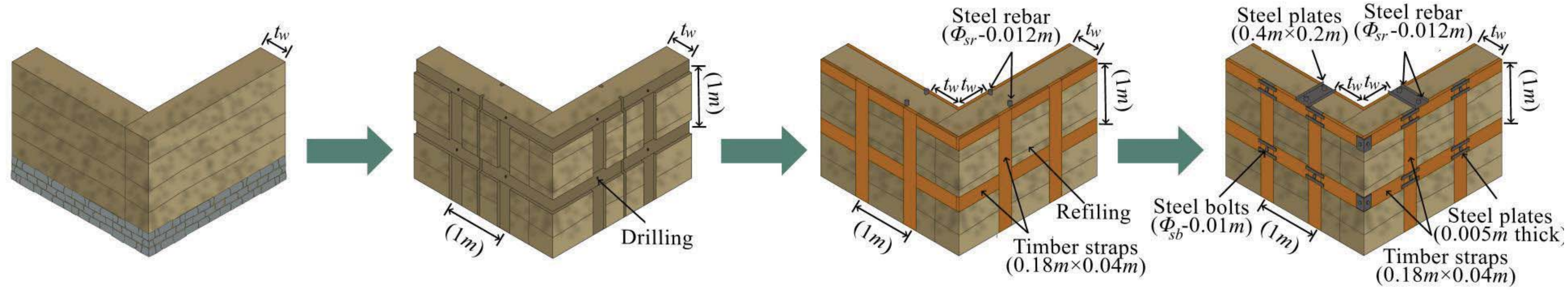
Tie the bamboos and the wall plate as shown

Final outcome

t_w= thickness of wall, Φ_{sw}= diameter of steel wire, Φ_b = diameter of bamboo

Figure 5.22: Strengthening existing rammed earth buildings using bamboo externally vertically

EXTERNAL TIMBER STRAPS



Rammed earth wall

Make grooves at 1m intervals and drill holes as shown

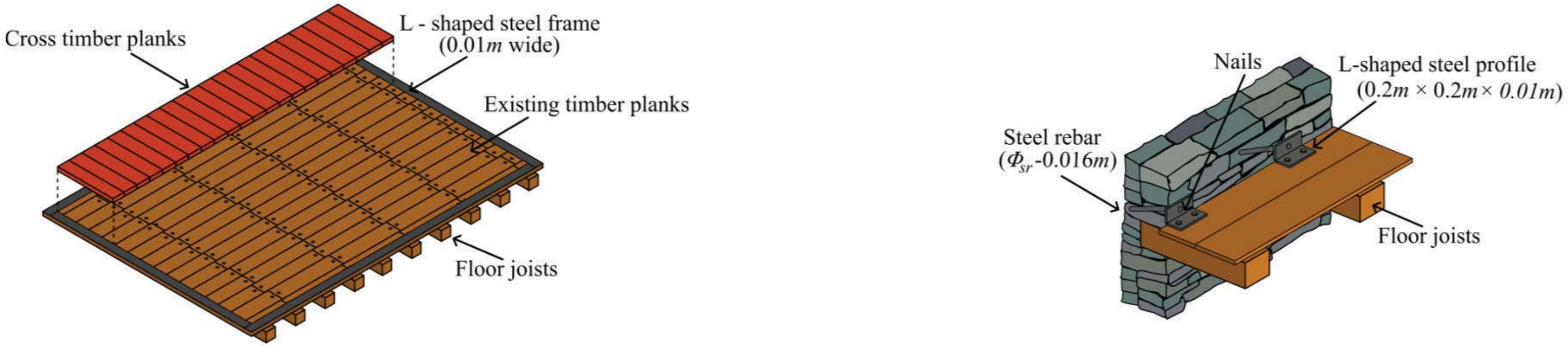
Place timber straps and steel rebars of diameter 0.012m

Place steel plates and bolt them to timber straps and steel rebars

t_w= thickness of wall, Φ_{sr}= diameter of steel rebar, Φ_{sb} = diameter of steel bolt

Figure 5.23: Strengthening existing rammed earth buildings using timber straps

IMPROVING EXISTING FLOOR RIGIDITY



Strengthening of floor using cross timber planks

Floor-to-wall connection

Note: L - shaped steel profile shall be connected to walls by steel rebars (Φ_{sr}-0.016m) at 0.5m interaval. This connection shall be used for the mentioned strengthening measure.

Φ_{sr}= diameter of steel rebar

Figure 5.24: Improving the existing floor rigidity using timber planks

IMPROVING IN-PLANE RIGIDITY OF THE ROOF TRUSS

Sloping roof without bracing

Trussed roof without bracing

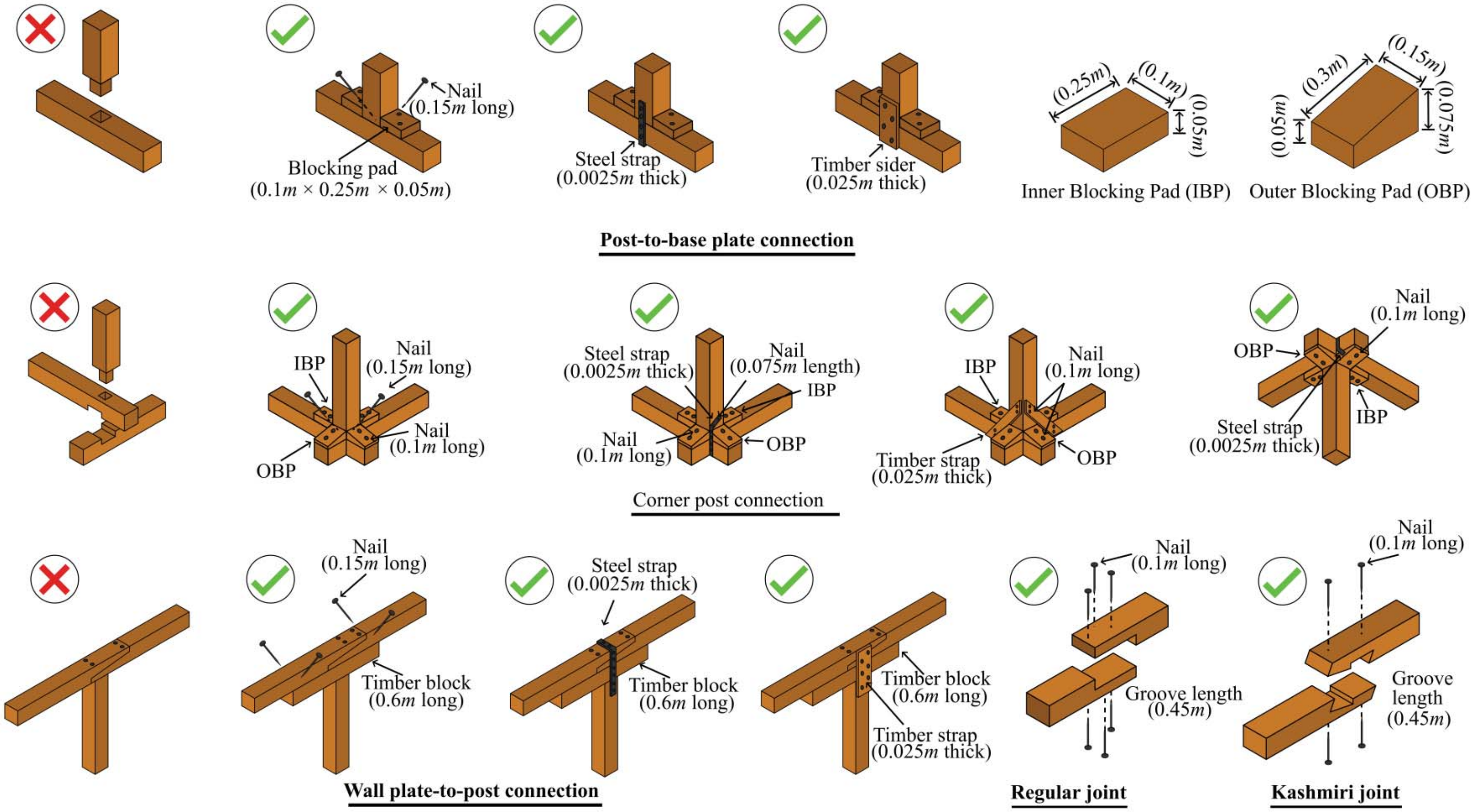
Trussed roof with cross-bracings

Hipped roof without bracing

Hipped roof with cross-bracings

Figure 5.25: Improving the existing roof rigidity using timber/metal cross-bracings

IMPROVING TIMBER FRAME CONNECTIONS



Note: For wall plate-to-post connection, additional timber block (capital) of minimum 0.1*m* thickness & 0.6*m* length shall be used.

Figure 5.26: Improving timber-frame connections using blocking pads/metal strips

IMPROVING TIMBER ROOF CONNECTIONS

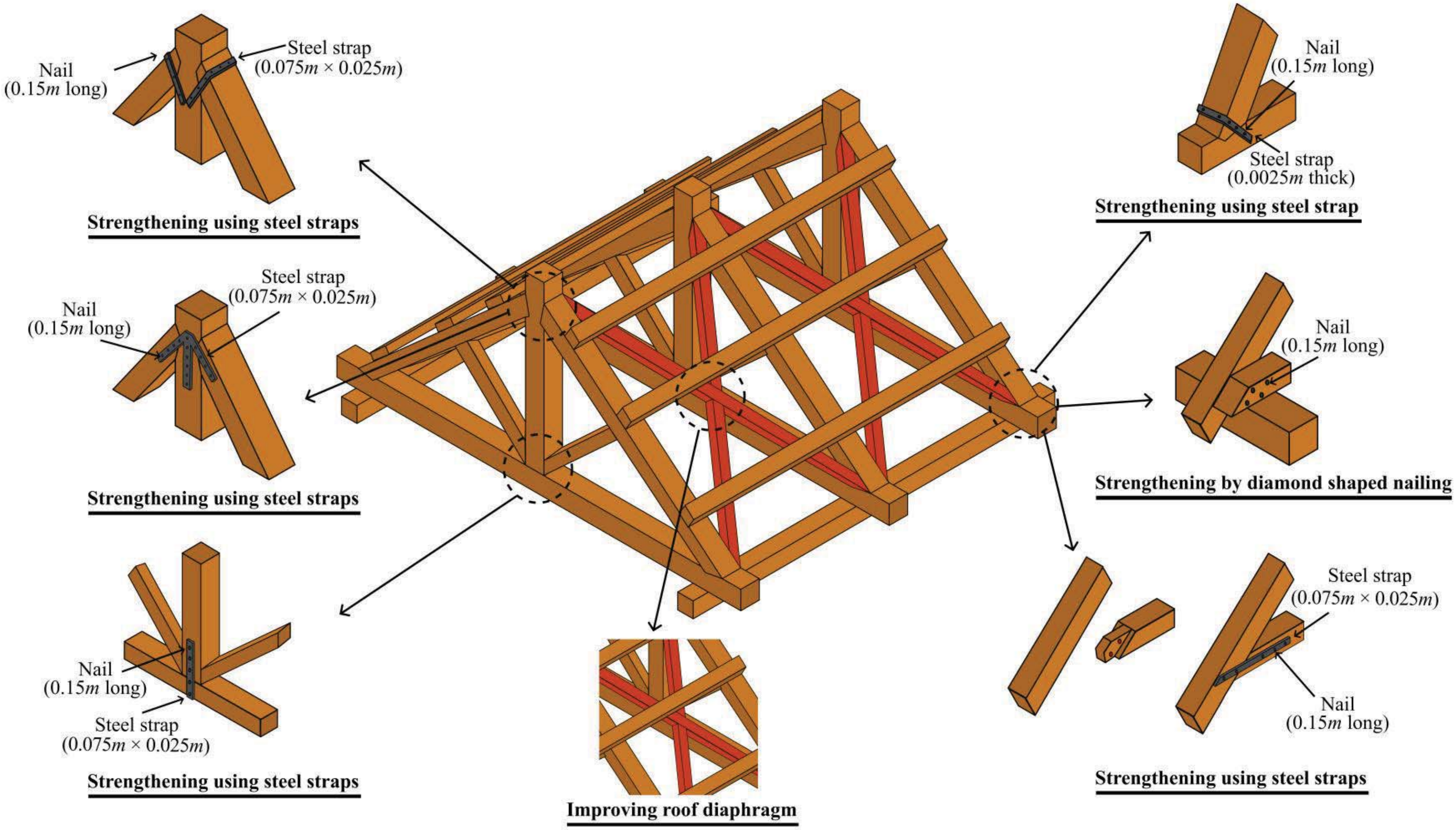
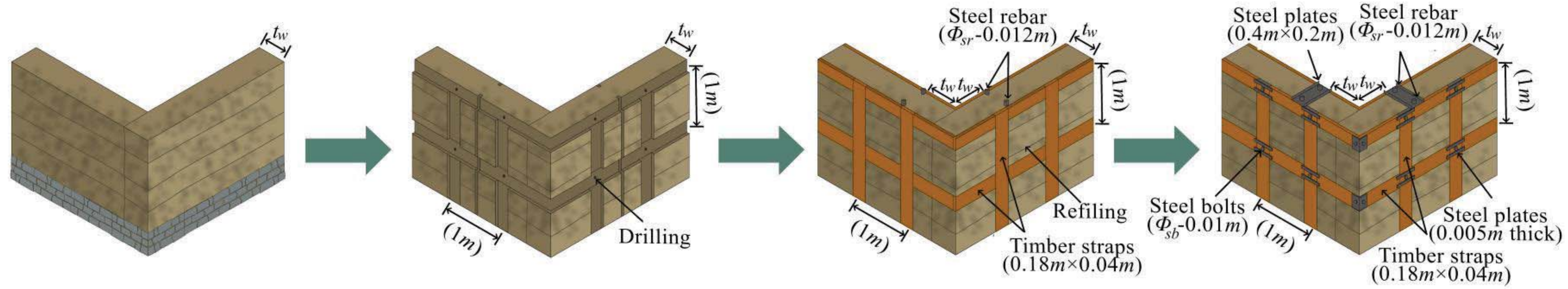


Figure 5.27: Improving timber-roof connections using timber boards/nails/metal strips

5.4 MODERN METHODS FOR IMRPOVING EARTHQUAKE RESISTANCE OF TRADITIONAL BUILDINGS

EXTERNAL WIREMESH REINFORCEMENT



Rammed earth wall

Make grooves at 1m intervals and drill holes as shown

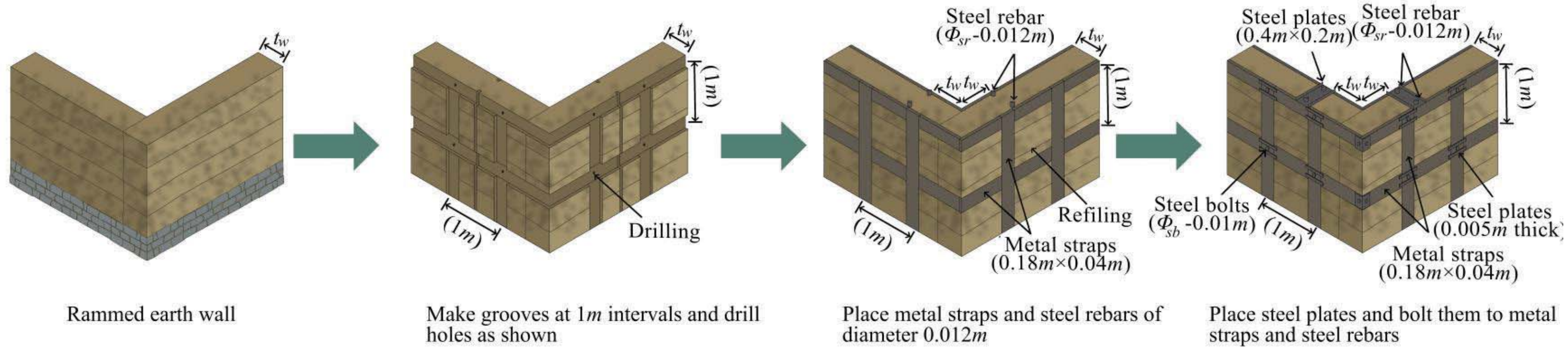
Place timber straps and steel rebars of diameter 0.012m

Place steel plates and bolt them to timber straps and steel rebars

t_w= thickness of wall, Φ_{sr}= diameter of steel rebar, Φ_{sb} = diameter of steel bolt

Figure 5.28: Strengthening existing rammed earth buildings using wire mesh reinforcement

EXTERNAL METAL STRAPS

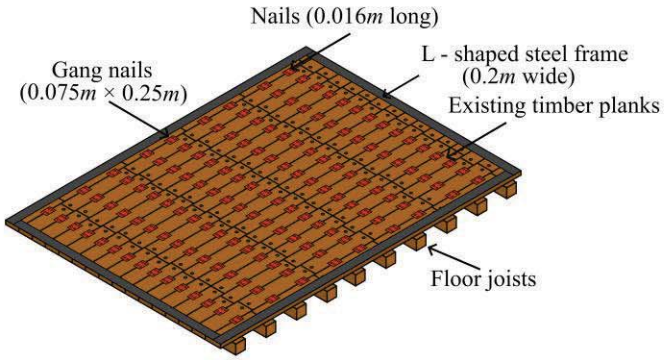


Note: The yield strength of the metal strap shall be minimum 420 N/mm^2

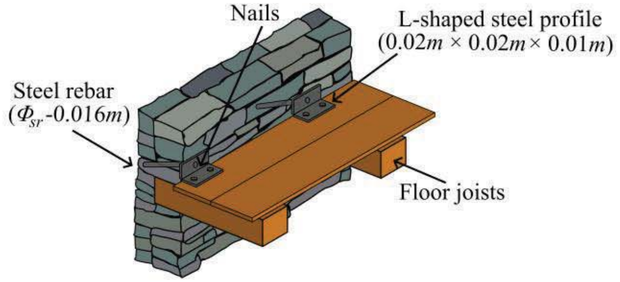
t_w= thickness of wall, Φ_{sr}= diameter of steel rebar, Φ_{sb} = diameter of steel bolt

Figure 5.29: Strengthening existing rammed earth buildings using metal straps

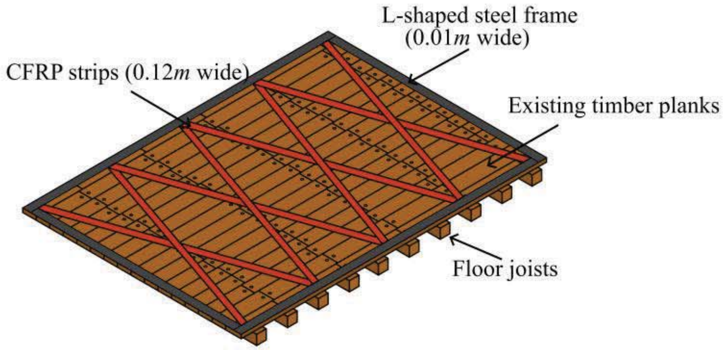
IMPROVING EXISTING FLOOR RIGIDITY



Strengthening of floor using 0.0015m thick gang nails



Floor-to-wall connection



Strengthening of floor using CFRP strips

Characteristics of CFRP strips and epoxy glue

Characteristics of Epoxy glue			
Viscocity at application (mPas)	3760	**Compressive strength (MPa)**	103
Working time (min)	30	**Flexiuon strength (Mpa)**	93
Proportion A/B	2/1	**Modulus of elasticity (MPa)**	3140
Tensile strength (Pa)	64	**Bond strength**	Timber shear rupture
Characteristics of CFRP strips			
Fiber content (%)	65	**Laminate width (mm)**	120
Effective thickness (mm)	1	**Maximum elongation (%)**	1.44
Tensile strength (MPa)	2850	**Density (gm/cm^3)**	1.6
Modulus of elasticity (GPa)	175	**Application temparature (C°)**	-40 to 130

Note: L - shaped steel profile shall be connected to walls by steel rebars (Φ_{sr} - 0.016*m*) at 0.5*m* interaval. This connection shall be used for both mentioned strengthening measures.

Φ_{sr} = diameter of steel rebar

Figure 5.30: Improving the existing floor rigidity using CFRP straps/Gang nails

CHAPTER 6

SUMMARY

Even though traditional building practices have existed for many centuries, minimal literature is available that investigates and documents traditional building practices of the study region. Limitations on the construction material, lack of skilled artisans knowing traditional construction, and lack of knowledge to strengthen traditional buildings have recently led to a considerable decline. A detailed field survey has been conducted to obtain better insights into siting, architectural features, structural features, soil conditions and foundations, visual conditions, and maintenance of traditional building practices of the study region. The seismic vulnerability of the existing traditional buildings prevalent in the study region is assessed qualitatively, and their earthquake-resilient and vulnerable features are highlighted in this study. Based on the observed intrinsic features in traditional buildings, Kath-Kunni, Thathara, Dhajji-Dewari, Taq, and Assam-type buildings in the study region are categorized as earthquake-resilient, whereas Rammed Earth buildings are classified as earthquake-vulnerable. The above conclusion has been obtained based on the qualitative analysis of the observed features during the field surveys in the study region. An attempt has been made to provide recommendations to construct earthquake-resilient traditional buildings and also to strengthen the earthquake-vulnerable features in traditional buildings of the study region. From the conducted study, the following significant conclusions can be drawn:

1. Kath-Kunni, Thathara, Dhajji-Dewari, Taq, and Assam-type traditional buildings incorporate multiple earthquake-resilient features into their siting and building architecture. These earthquake-resilient features include the selection of a building site with flat topography and rocky strata, selecting a robust structural plan shape (rectangular plan shape with an aspect ratio not exceeding 3), small story heights, low building height-to-width ratio (wider base), small sizes of openings, placement of the openings away from wall edges/corners, and strengthening the surroundings of the openings with timber diagonal bracings. Mostly, these features comply with the current Indian seismic standards/guidelines on low-strength masonry/timber buildings. The presence of these architectural features in the centuries older traditional buildings highlights their well-understood importance by the Himalayan communities for achieving earthquake resilience.

2. Kath-Kunni, Thathara, Dhajji-Dewari, Taq, and Assam-type traditional buildings have multiple structural features adding to their earthquake resilience. These features include thick load-bearing walls and or well-connected frame system, high structural wall plan density (typically about 20-30%), distribution of walls in two orthogonal (horizontal) directions, use of multiple timber bands along with the height of the wall to ensure an integral box action and deformability, multiple load paths (redundancy) in the structural system, interlocking of timber bands/floor beams at the wall junctions through loose-fit connections, flexibility in the building elements and connections, arrangements to tie the floors/roofs with the walls, and use of light-weight materials/partitions and or thinner walls (particularly in walls at upper floors) to reduce the

seismic mass and avoid overturning of the building. These features in Kath-Kunni, Thathara, Dhajji-Dewari, Taq, and Assam-type traditional buildings make them at least equivalent (if not superior) to the buildings constructed using similar materials following the existing Indian standards.

3. The study region's rammed earth traditional building practices are seen with multiple earthquake-vulnerable features. The siting and architectural features that severely compromise their earthquake safety include building construction on steep unstable slopes or on top of a hill, the presence of large wall openings, the concentration of openings in one of the exterior walls leading to asymmetric stiffness distribution and inducing torsion, placement of openings close to wall edges, use of complex (irregular) plan shapes, and re-entrant corners. On the other hand, the structural features that make them further susceptible to failure/collapse under seismic actions include the absence of wall-to-foundation connections, absence of wall-to-wall connections, limited in-plane shear and bending strength, limited stiffness of the walls due to large openings, lack of seismic bands at the sill, lintel, and eave level, absence of the floor/roof-to-wall connections, floor/roof flexibility resulting in increased susceptibility of load-bearing walls to out-of-plane failure/collapse.

4. Kath-kunni and Thathara traditional buildings extensively use semi-dressed to dressed stones in thick load-bearing walls and heavy-weight stone slates in roofing. Thus, both Kath-kunni and Thathara buildings possess high seismic weight and attract higher seismic forces compared to other traditional systems. In contrast, the Dhajji-Dewari and Assam-type buildings have timber frames as primary systems along with relatively thinner walls compared to Kath-kunni and Thathara traditional buildings. Hence, Dhajji-Dewari and Assam-type buildings possess a higher strength-to-weight ratio, which is desirable for earthquake resistance.

5. Though not directly investigated in this study, the Kath-Kunni, Thathara, Dhajji-Dewari, Taq, and Assam-type traditional buildings extensively use stones, stones/bricks in mud mortar, and timber as the construction materials. Past research showed that the structures made up of the above-mentioned construction materials possess high damping ratio. In the undamaged states, the damping ratio of traditional buildings is expected to be of the order of 10% of critical – contrary to the 5% damping ratio for contemporary materials, recommended by seismic design codes. Further, in the damaged state, the damping ratio for these traditional buildings can increase and typically it could range between 20-30%. As a result, these traditional buildings are subjected to relatively smaller seismic forces (typically, the reduction is about 20-50%) compared to their contemporary counterparts, which is also beneficial for their earthquake resistance. In contrast, rammed earth building possesses a relatively low damping ratio (typically 3-4% of the critical in the undamaged state), thus attracting higher seismic forces (typically, the increase is about 20%) compared to their contemporary counterparts, hence, detrimental to their earthquake resistance.

6. A structural system classification of the studied traditional buildings is presented. This structural classification includes the observed variations in the field surveys, such as the arrangement of a building foundation on the slope and slope retaining system (if any), building height, load-bearing system, floor and roof systems, and foundations. The developed structural classification

can further serve as the supporting information to conduct detailed seismic vulnerability and risk assessment for the study region.

7. Among the identified traditional buildings Kath-Kunni, Thathara, Dhajji Dewari, and Taq buildings (mainly either due to high cost or scarcity of the timber) are not practiced for newer constructions, whereas Assam type and Rammed earth buildings are still practiced in the region of their prevalence. Accordingly, seismic safety measures are suggested for further improving earthquake resistance of existing Kath-kunni, Thathara, Dhajji-Dewari, Taq, and Assam-type buildings.

8. A ready-to-use guidance document has also been prepared to construct the new traditional buildings. The document includes sketches describing the selection of a building site, plan shape, elevation shapes, sizes and placement of the openings, placement of walls, etc. Further, suitable measures are suggested to improve walls' in- and out-of-plane capacities, the integrity of the buildings, wall-to-wall connections, and floor/roof-to-wall connections for rammed-earth buildings. Seismic safety measures are also suggested to improve the earthquake resistance of existing Kath-kunni, Thathara, Dhajji Dewari, Taq, and Assam-type buildings by improving the in-plane rigidity of floors and roofs.

CHAPTER 7

RECOMMENDATIONS

1. It is foreseen that the work presented herein will prompt the interest of academicians and practitioners to study the traditional buildings further experimentally and numerically and develop guidelines and standards for detailed seismic assessment and up-gradation of both the existing and new traditional structures.

2. Unavailability of timber due to joint effects of the Indian Forest Act (1927) and subsequent strict government norms for tree cutting have been identified as one of the root causes for the extinction of the traditional earthquake-resilient building practices of the study region. It is strongly recommended that wood farming should be promoted, which could greatly help in fulfilling the dual objectives of sustainable and earthquake-resilient housing in the Indian Himalayas.

3. It is recommended that the NDMA and SDMAs organize training programs for local artisans, NGOs, and Civil societies to adopt seismic resilient practices in local construction using locally available materials. State/region-specific building typologies, as identified in this report, can be chosen for promotion in different states.

CHAPTER 8

THE WAY FORWARD

The Indian Himalayan region has several traditional building practices (Table 8.1). Among the listed traditional building systems, the detailed investigations conducted in this study are limited to structural systems Kath-kunni, Thathara, Rammed earth, Dhajji-Dewari, Taq, and Assam-type buildings, which came into existence at least two centuries before the present time. Therefore, further efforts are required to document and investigate the other traditional buildings of the Indian Himalayan region. Along similar lines, there exist traditional buildings in other parts of India, e.g., the Bhonga house in Gujarat which should also be documented and investigated in detail.

Table 8.1: List of traditional building systems of the Indian Himalayan region

S. No.	Traditional building type	Union Territory /State of Prevalence
1.	Kath-kunni (Koti-banal) buildings	Uttarakhand and Himachal Pradesh
2.	Thathara buildings	Himachal Pradesh
3.	Rammed earth buildings	Ladakh and Himachal Pradesh
4.	Dhajji-Dewari buildings	Jammu and Kashmir
5.	Taq buildings	Jammu and Kashmir
6.	Assam Type buildings	Assam, Sikkim, and Meghalaya
7.	Nyishi buildings	Arunachal Pradesh
8.	Apatani buildings	Arunachal Pradesh
9.	Adi buildings	Arunachal Pradesh
10.	Mizo buildings	Mizoram
11.	Tong buildings	Tripura
12.	Mud house	Tripura
13.	Lepcha buildings	Meghalaya
14.	Garo buildings	Meghalaya
15.	Naga buildings	Nagaland
16.	Yumjao buildings	Manipur

The seismic vulnerability assessments conducted in this study are based on the qualitative analysis of the siting, architectural, structural, foundation, and visual conditions (observed during the field surveys) of traditional buildings and comparing them with the fundamental principles of earthquake safety established in the literature and relevant codes of practice. Further efforts are required to conduct detailed quantitative seismic vulnerability assessments of traditional buildings. Hence, extensive experimental investigations shall be conducted to characterize the materials used in traditional buildings, and their behavior under reversed cyclic loadings should be understood. Full-scale structural testing shall be taken up in the near future to further improve the understanding of the seismic behavior of traditional buildings. Detailed assessments using state-of-the-art nonlinear modeling techniques shall be conducted to estimate the expected damage in traditional buildings. Efforts are also required to experimentally investigate and develop simple methods/techniques to strengthen the existing traditional buildings.

CHAPTER 9

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PROJECT TEAM

The individuals who contributed to the work presented in this report are listed below:

List of Investigators:

1. Dr. Mitesh Surana, Assistant Professor, Department of Civil Engineering, IIT Ropar
2. Dr. Putul Haldar, Assistant Professor, Department of Civil Engineering, IIT Ropar
3. Dr. Yogendra Singh, Professor, Department of Earthquake Engineering, IIT Roorkee
4. Dr. Jayanta Pathak, Professor, Assam Engineering College, Guwahati

List of Students/ Project Staff/Lab Staff:

1. Mr. Dharmil Baldev, Research Scholar, Department of Civil Engineering, IIT Ropar
2. Mr. Tuhinanshu Modgil, UG Student, Department of Chemical Engineering, IIT Ropar
3. Ms. Sruthi J S, Former Research Intern, Department of Civil Engineering, IIT Ropar
4. Mr. Argha Ghosh, Former JRF, Department of Civil Engineering, IIT Ropar
5. Mr. Ankur Jain, Research Scholar, Department of Civil Engineering, IIT Ropar
6. Ms. Oshin Arora, Research Scholar, Department of Civil Engineering, IIT Ropar
7. Mr. Vipin Kumar, Senior Lab Assistant, Department of Civil Engineering, IIT Ropar
8. Mr. Shikhar Prakash, Research Scholar, Department of Earthquake Engineering, IIT Roorkee
9. Mr. Kamal Kumar, Research Associate, Department of Earthquake Engineering, IIT Roorkee
10. Mr. Zeeshan Manzoor Bhatt, Research Scholar, Department of Earthquake Engineering, IIT Roorkee
11. Mr. Tajul Islam, Research Scholar, Department of Earthquake Engineering, IIT Roorkee
12. Mr. Ravi Shastri, M.Tech. Student, Department of Earthquake Engineering, IIT Roorkee

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