Seismic Performance of Buildings during the November 2023 Earthquake in Jajarkot, Nepal

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Abstract: On November 3, 2023, a local magnitude M_L 6.4 (moment magnitude, M_W 5.7) earthquake struck the Ramidanda epicenter (28°50'24'' N, 82°11'24'' E) in Jajarkot, Nepal, at 11:47 p.m. local time (18:02 GMT), with a maximum intensity VI on the Mercalli Intensity Scale. Continuous aftershocks further devastated partially affected villages in Jajarkot, West Rukum, and Salyan. This seismic sequence stands as one of the most destructive earthquakes in Nepal since the 2015 Gorkha Earthquake, with a total death toll of 154 and over 366 people injured. The earthquake caused the complete collapse of 26,557 houses, while 35,455 houses were partially damaged. Postearthquake reconnaissance showed that the damage to masonry buildings in the affected areas was mainly due to poor construction quality, degraded construction materials, and noncompliance with codal provisions. Although reinforced concrete buildings in proximity to the main shock epicenter suffered minor damages, many of the affected structures were found to lack appropriate design or construction adherence to the national building code of Nepal. This paper, based on the postearthquake field visit, aims to present the structural damages in buildings incurred during the earthquake, discussing case histories of the affected buildings, their patterns, and the failure mechanisms. The findings highlight the critical need to enforce rigorous building codes and standards to mitigate seismic risk in vulnerable regions like Nepal. **DOI: 10.1061/JPCFEV.CFENG-4902.**

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Introduction

On Friday, November 3, 2023, a shallow earthquake with a moment magnitude (M_W) of 5.7 and focal depth of 10 km occurred at the Ramidanda Epicenter of Barekot Rural Municipality in the Jajarkot District, Nepal (Fig. 1). Following the earthquake, a series of aftershocks occurred, including two aftershocks with magnitudes of M_W 4.0 and M_W 5.3 within three days of the mainshock. The midnight earthquake caused the total death of 154 individuals. The earthquake fully damaged over 26,500 houses and partially damaged over 35,000 houses in districts including Jajarkot, Rukum West, and Salyan (Subedi et al. 2024). In addition to structural damage to buildings, roads, bridges, and heritage sites were also adversely affected. The earthquake was perceptible in Western Nepal and Northern India, including New Delhi (Sharma 2023). The Jajarkot Earthquake is the deadliest seismic event in Western Nepal since 1505, though the 2015 Gorkha Earthquake (M_W 7.8) caused over 8,500 deaths and 22,000 injuries, and damaged more than 5 million houses, resulting in a monetary loss of about 7 billion USD in Central and Eastern Nepal (Acharya et al. 2022; Badal and Motra 2023).

Such earthquakes, causing significant human casualties and infrastructure damage, underscore the vulnerability of communities to natural disasters. Studying postearthquake building behavior is crucial for enhancing resilience of structures and infrastructures in similar future events. Various postearthquake studies have been done worldwide to assess the damage of buildings. Recent earthquakes that have caused extensive damage to unreinforced masonry buildings are mentioned in Table 1.

Following the 2015 Gorkha Nepal Earthquake, the structural performance in the central and eastern regions is well-documented, whereas documentation for the western region is sparse due to negligible shaking in that area. Despite numerous small earthquakes occurring in Western Nepal in recent years, this seismic event stands out as one of the most destructive since 1505 ($M_s \sim 8.2$), as depicted in Fig. 1. The last significant earthquake to strike Western Nepal, causing extensive damage, occurred in 1505. Currently, Western Nepal has 2,747,739 households, housing a population of 11,971,700 people. Most of these houses are generations old and remained untested for earthquake resilience until the Jajarkot Earthquake. Even a relatively moderate earthquake has caused the complete collapse of more than 26,000 houses. Numerous studies have cautioned about a significant strain build-up in the region, predicting the occurrence of a strong earthquake ($M_W > 6$) in Western Nepal (Srivastava et al. 2015). In this regard, this seismic event enables the assessment of the structural performance of residential and heritage buildings in the region, aiding in the preparedness for potential strong earthquakes in the future.

Postearthquake building damage assessment helps in updating and implementing building codes by providing real-world data on

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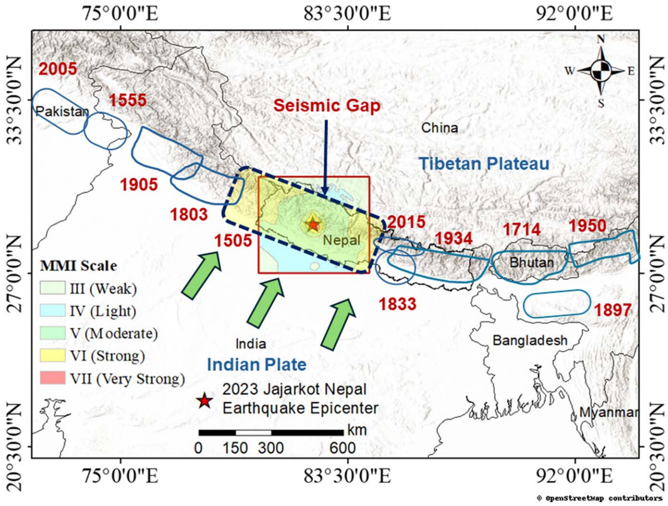

Fig. 1. Map showing historical earthquakes (blue color outlines) and seismic gaps in Western Nepal (black dotted outline), alongside the location map of the 2023 Jajarkot Earthquake with its epicenter and intensity distribution. (Base map © OpenStreetMap contributors.)

the performance of structures during an earthquake (Ilki and Celep 2012; Marshall et al. 2013; Nwadike et al. 2019; Shakya et al. 2021). Additionally, assessments can identify successful design and construction practices that can be incorporated into building codes to enhance their effectiveness in mitigating earthquake damage (Sharma et al. 2016). Postearthquake reconnaissance aids in uncovering new insights and deepening understanding of natural phenomena, which helps in mitigating the destructive impacts of earthquakes on individuals and the built environment (Bardet and Liu 2010). Overall postdisaster reconnaissance studies are crucial for evaluating the performance of buildings and infrastructure, spotting vulnerabilities, and improving construction practices and safety measures. They uncover weaknesses exposed by moderate earthquakes, guiding adjustments to better handle stronger seismic events. In areas with seismic gaps like Western Nepal, these studies provide insights into potential future earthquakes by analyzing recent damage and failures, thereby enhancing risk assessments and informing preparedness and mitigation strategies to lower the risk of future disasters.

The authors undertook a field reconnaissance following the earthquake, with the objective to analyze the factors contributing to damage patterns in diverse structures, encompassing residential and heritage buildings. This paper discusses the structural aspects of the damages caused by the Jajarkot Earthquake, presents insights into the categorization of buildings in Nepal, and outlines the performance of different building categories, primarily masonry, and some reinforced concrete. Based on the prompt field survey of the earthquake affected area, this paper can offer valuable insights into reconstruction efforts and the design of earthquake-resistant buildings in Western Nepal.

Seismo-Tectonic Aspects and Ground Motion

Nepal is located in the middle of the Himalayan Range, which is one of the most active seismic regions in the world (Chiaro et al. 2015;

Table 1. Major recent earthquakes that have caused extensive damage to masonry buildings

Earthquake	Structural performance
Darfield Earthquake, 2010, New Zealand (M_w 7.1) Ingham and Griffith (2010)	• Damage patterns in unreinforced masonry buildings during major earthquakes included toppled chimneys, parapets, failed gables, unsecured face-loaded walls, and in-plane masonry frame damage. • Seismically retrofitted structures performed well
Maule Earthquake, 2010, Chile (M_w 8.8) Astroza et al. (2012)	• Several three- and four-story masonry buildings, reinforced and partially confined, experienced extensive damage, and two three-story partially confined buildings collapsed. • The main causes of damage were out-of-plane failure, in-plane shear cracks, substandard quality construction materials, and flaws in reinforcement ties. • The majority of one- and two-story single-family masonry homes, along with three- and four-story confined masonry structures, did not sustain any damage.
Tripura Earthquake, 2017, Bangladesh (M_w 5.6) Saha et al. (2020)	• Old masonry buildings, non-engineered rammed earth, and adobe houses as well as multiple reinforced concrete structures, experienced significant damage. • Nonengineered rammed earth houses with CGI or straw roofs, along with buildings situated near slopes, experienced significant damage due to insufficient foundation support. Despite this, houses that utilized bamboo as wall reinforcement demonstrated effectiveness during the earthquake.
Hindu Kush Earthquake, 2015, Pakistan (M_w 7.5) Ismail and Khattak (2019)	• The earthquake primarily damaged seismic-deficient unreinforced masonry (URM) buildings. • Typical failures included toppled minarets, out-of-plane collapse of URM walls, and various types of cracking and settlement damage. • Most human casualties resulted from URM wall failures and subsequent roof collapses, with rural URM buildings near the epicenter suffering more intense damage than urban counterparts.
Turkey Earthquake, 2019 (M_w 5.2) Yön (2021)	• Despite its moderate magnitude, the earthquake caused significant failures, with many masonry buildings and adobe dwellings in Sivrice villages suffering severe damage. • Weak structural detailing of wall-to-wall and wall-to-roof connections, inadequate bonding of earthen roofs, and a lack of bond beams in structural walls were key factors contributing to the dwellings' damage.
Gorkha earthquake, 2015, Nepal (M_w 7.8) Whitney and Agrawal (2017), Okamura et al. (2015), Goda et al. (2015), and Sharma et al. (2016)	• Structural and nonstructural damages affected all prevalent structural systems, ranging from complete collapses to partial damage. • The damage in affected areas stemmed from structural and material deficiencies, compounded by local amplification and topographical effects. • Marginal construction practices, inferior building materials, aging structures, and continued use without repair were major contributors to extensive structural damage.

Sharma et al. 2016; KC et al. 2024a; Bhusal et al. 2023). The convergence between the Indian and Tibetan plates, commonly referred to as the Himalayan Collision, involves the subduction of Indian Plate beneath the Himalayan Region by approximately 4–5 cm/year (Sharma et al. 2016; Paul et al. 2001; Lavé and Avouac 2000; Liu et al. 2021), 2 cm/year (Avouac 2003; Ader et al. 2012) through a large fault called the Main Himalayan Thrust (MHT). This movement leads to the accumulation of elastic deformation energy that is periodically released by slipping along the MHT fault plane, resulting in devastating earthquakes in the area (Bilham et al. 2001; Feldl and Bilham 2006; Mugnier et al. 2013). Nepal has experienced several major earthquakes with magnitudes of 7.6 or greater, including those in 1255, 1408, 1505, 1833, 1934, and 2015 and several strong earthquakes since 1255 (Thapa 2018; Acharya et al. 2023a).

In the past 800 years, Central and Eastern Nepal have experienced at least four and possibly up to eight major earthquakes ($7 < M_W < 8$), as recorded by historical seismicity and trenching studies (Bollinger et al. 2016). Despite the historical recurrence of strong ($6<M_W < 7$) to mega earthquakes ($M_W > 8$) in Nepal showing an interval of 80 to 100 years, the last major earthquake to impact Western Nepal occurred in 1505, which ruptured a long portion of the Main Frontal Thrust (MFT) and was estimated to be around M_W 8.2 in magnitude (Kumar et al. 2006). The continuous convergence of the Indian Plate beneath the Eurasian Plate has resulted in a significant accumulation of strain energy in Western Nepal, stretching from Gorkha to the far western region. This phenomenon could lead to several mega earthquakes of magnitude greater than 8.0 (Bilham et al. 1997; Pandey et al. 1995). This seismic gap spanning over 500 years makes Western Nepal consistently susceptible to major earthquakes. The seismic gap in the area is depicted in Fig. 1. Between 1963 and 2006, the seismic events occurring in the Western Nepal Himalayan area exhibited fluctuations, ranging from elevated to subdued seismic phases (Paudyal et al. 2010). These occurrences are likely attributed to the Main Boundary Thrust (MBT) and the prevalent geological features within the area. The presence of a weakened Main Himalayan Thrust located beneath Tibet, along with the commencement of the Main Central Thrust, can be elucidated by the South Tibetan Detachment and the stress field aligning with Western Nepal (Paudyal et al. 2010). The most recent seismic event in Western Nepal occurred in Bajhang on October 3, 2023, with a magnitude of M_W 5, and was experienced in Bajhang, Kathmandu, and some parts of India.

The ground motion data for the November 3, 2023, Jajarkot Earthquake in Nepal is sourced from the nearest station to the epicenter, which is Bhimchula. The recorded ground motions at this station resulted in a peak ground acceleration (PGA) reaching up to 70 cm/s^2 (Subedi et al. 2024), lesser than the anticipated PGA derived from probabilistic seismic hazard analysis with a 10% probability of exceeding the 50 year period [NBC 105 (NBC 2020)].

Building Typology

Nepal is home to a wide variety of structures, each of which is distinguished by its own construction methods, typologies, and material choices. Common modalities include adobe, wooden, stone in mud mortar, brick in mud mortar, stone in cement mortar, brick in cement mortar, nonengineered reinforced concrete (RC), and engineered RC. Fig. 2 offers a succinct overview of the most prevalent building typology in visual representations. During the 2021 National Population and Housing Census, Nepal accommodated a population of 29,164,578 residing in 6,666,937 separate households. Notably, mud-bonded brick/stone masonry structures emerged as the most widespread across all regions, making it 30.67% of overall structures, 11.71% buildings are made up of bamboo. In contrast, urban areas like Kathmandu Metropolitan City exhibited a prevalence of cement-bonded brick and stone structures (29.79%) and cement concrete structures (28.94%).

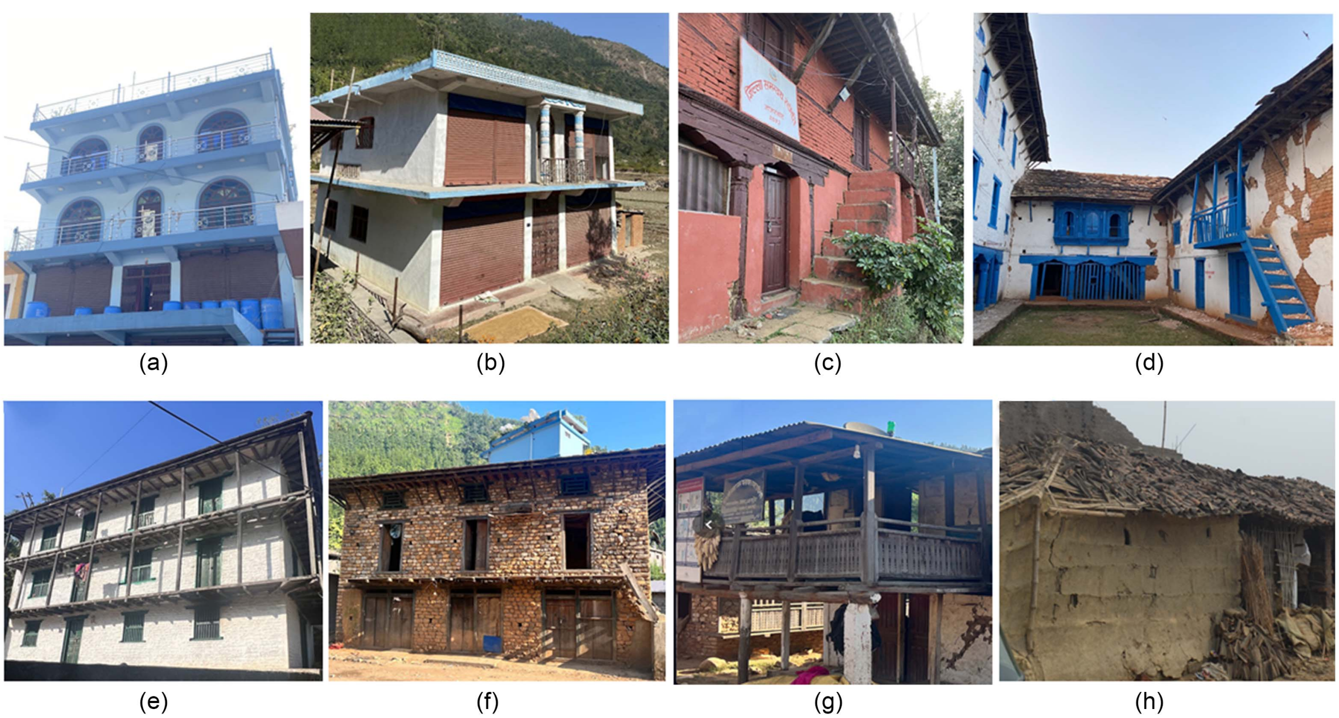

Fig. 2. Existing building types in Nepal: (a) engineered RC; (b) nonengineered RC; (c) brick in cement mortar; (d) brick in mud mortar; (e) stone in cement mortar; (f) stone in mud mortar; (g) wooden; and (h) adobe. (Images by Rajan KC.)

Fig. 3. Location map displaying field visit area. (Base map image © Google, Image ©2024 Airbus; images by Rajan KC.)

Nepal is a low-income country with rapid pace of urbanization, where masonry buildings in rural areas often utilize sun-dried or fired bricks and stone walls held together by mud mortar, incorporating wooden frames (KC et al. 2024b). Primarily located in rural regions, these constructions are distinguished by flexible roofing and flooring, coupled with restricted structural strength. There has been an increasing trend in using cement mortar for constructing brick or stone structures. Closer to forested areas, structures made of wood, supported by timber pillars crafted from tree trunks, and featuring walls constructed from wooden planks or bamboo netting coated with cement or mud plaster are more prevalent.

A contemporary adaptation in Nepalese architecture is RC construction, a trend that has been prominent since the late 1970s. An essential element of this approach is the use of RC moment-resisting frames comprising concrete beams and columns reinforced by slabs for floors and roofs. However, a considerable number of conventional RC buildings in Nepal are nonengineered, meaning they do not adhere to the seismic regulations specified in the Indian standard code; consequently, they lack the necessary resilience during earthquakes.

Field Observations

The field reconnaissance in the aftermath of the earthquake was conducted by the authors from November 6 to 9 in the three most affected districts: Jajarkot; West Rukum; and Salyan. The authors comprehensively analyzed observations, drawing on experiences from the 2015 Gorkha Earthquake and existing literature. Questionnaires were also conducted with homeowners and local authorities about the workmanship and compliance with building codes. The survey evaluated the performance of structures made of masonry and RC, which were impacted by the 2023 Jajarkot Earthquake in Nepal in the Jajarkot and West Rukum districts (Fig. 3). This section presents the observed damage patterns in masonry and RC buildings following the earthquake, with the possible underlying mechanics behind these occurrences.

Damage to Masonry Buildings

The prevalent construction style in the heavily impacted rural regions of Jajarkot was unreinforced stone masonry, which either completely collapsed or suffered extensive damage. A similar trend was observed during 2015 Gorkha Earthquake in Nepal (Acharya et al. 2023b; Parajuli et al. 2020; Khadka and Shakya 2021; Pan et al. 2018, 2024). Two of the districts most affected by the Jajarkot Earthquake, namely, Jajarkot and West Rukum, have 95.63% and 90.87%, respectively, of houses with mud-bonded brick/stone foundations. These structures are deficient in the ductile components essential for seismic resilience, leading to a tendency for brittle failure, which is a common issue in masonry buildings not reinforced with ductile materials. This section highlights the damage mechanisms in these types of structures in Western Nepal. Fig. 4 provides an overview of some masonry buildings nearer to the epicenter of the main shock in Jajarkot, Nepal, depicting overall devastation. The failure of these buildings can be attributed to several factors, including the weak bonding of walls made from boulders or rubble directly collected from riverbanks and held together with mud mortar or, in some cases, dry-stacked masonry units. Additionally, a lack of strong connections between floors and walls has also been observed in this case.

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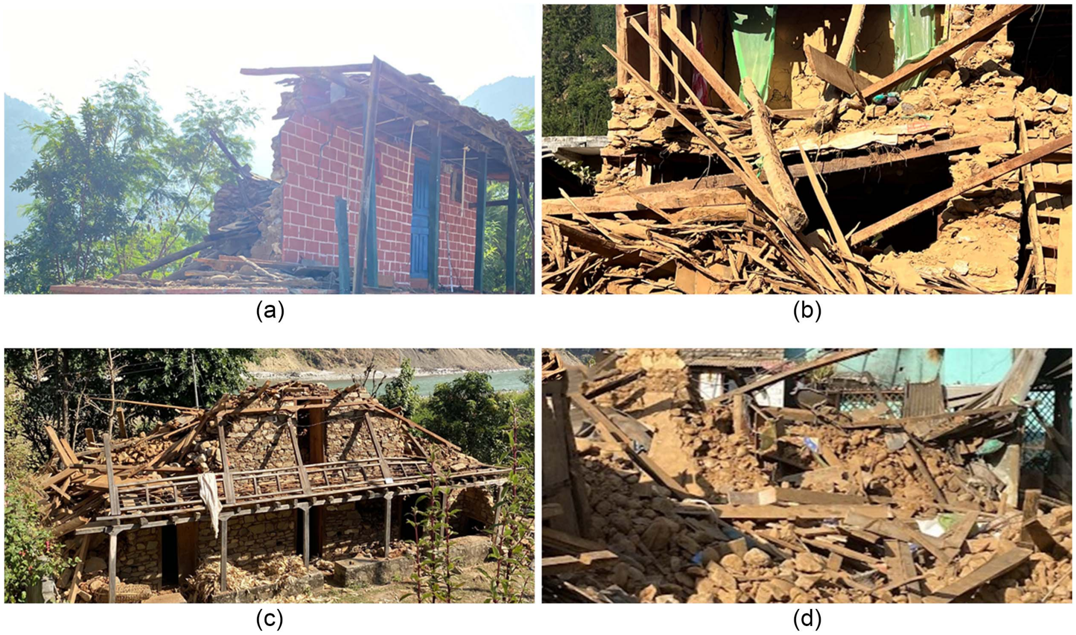

Fig. 4. Complete collapse of buildings during 2023 Jajarkot Earthquake in Nepal (28’41'54"N, 82’13'48"E). (Images by Rajan KC.)

Failure Mechanisms

Separation of the Wall. The existence of voids within structural walls significantly hinders their ability to bear bending and shearing forces during earthquakes. Further, in the construction of thick walls, the absence of through-stones can lead to vertical separation in the wall. The utilization of ineffective mud mortars and inadequately integrated multileaf stone walls also resulted in the separation of wall layers, posing a potential risk of building collapse. Figs. 5(a and b) illustrate the vertical separation of the wall caused by the absence of through stones. Figs. 5(c–e) show the schematic wall section and plans with through (key) stones.

Out-of-Plane Failure. Fig. 6(a) shows the out-of-plane failure observed in a masonry structure, leading to the collapse of a single side of the wall; Fig. 6(b) shows the out-of-plane failure initiating the roof collapse. This failure is attributed to insufficient bonding between adjacent walls [as illustrated in Figs. 6(c and d)]. The phenomenon becomes noticeable when a seismic wave travels along the crest surface. The wall face perpendicular to the seismic wave direction does not produce substantial lateral force, primarily due to its lower width with a lower moment of resistance. Buildings featuring extended facades, flexible floor structures, and inadequate connections between return walls often undergo partial or complete overturning or instability of load-bearing walls. This can result in moderate to severe damage and, in many cases, partial or full building collapse. Most buildings in Jajarkot experiencing out-of-plane failures had weak return wall connections, leading to separation and subsequent failure of entire walls. Additionally, almost all observed buildings had nonexistent connections between diaphragms and walls.

Gable Wall Failure. The failure of gable walls is illustrated in Fig. 7(a). The collapse of gable walls could potentially initiate the failure of the adjacent shorter lateral walls, as depicted in Fig. 7(b). The frequent out-of-plane failure of gables occurred because of inadequate connection between the gable and the roof. Constructing gables using lighter materials such as wood can effectively mitigate these failures, enhancing structural integrity.

Vertical Cracks Near the Corner. Inadequate connections or a lack of shear transfer between the walls and floors can lead to poor structural integrity, resulting in the development of vertical cracks. Uneven settlement of the foundation may contribute to this issue, although no noticeable subsidence was observed around or near the

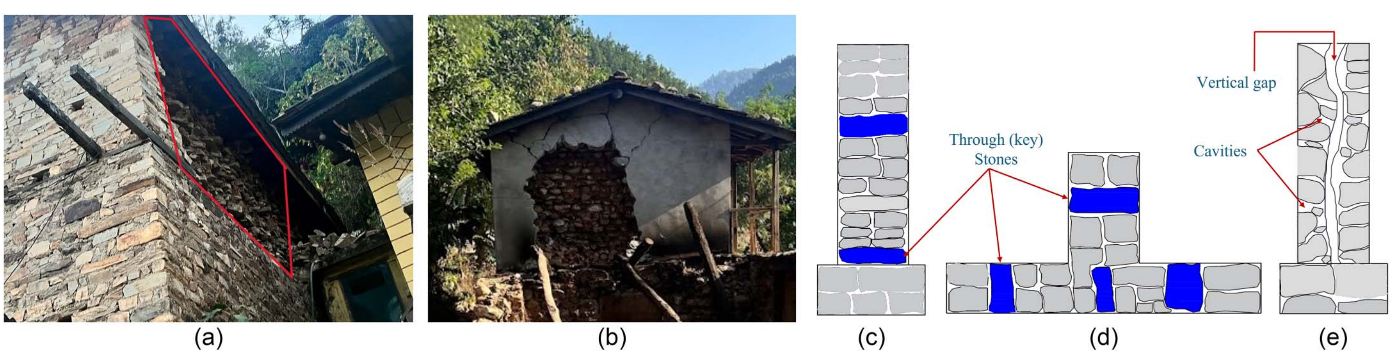

Fig. 5. (a and b) Separation of the wall along the vertical plane resulted from insufficient bonding between the inner and outside wall (28°41′56″ N, 82°16′46″ E); (c) wall section including key stones; (d) wall plan including key stones; and (e) wall section without key stones. [Images (a and b) by Mandip Subedi.]

(a) (b) (c) (d)

Fig. 6. (a) Out-of-plane failure of the masonry buildings made up of round-shaped stone (collected directly from the river); (b) out-of-plane failure initiating roof collapse (28°41′57″ N, 82°16′44″ E); (c) schematic illustration showing out-of-plane failure; and (d) in-plane failure mechanism. [Images (a and b) by Rajan KC.]

(a) (b)

Fig. 7. (a) Gable wall failure due to lack of gable band; and (b) gable wall failure initiating collapse of the shorter wall (28°42′42″ N, 82°16′59″ E). (Images by Mandip Subedi.)

buildings. Fig. 8 shows the common types of failure patterns in masonry structures subjected to in-plane loads.

Additionally, out-of-plane bending, induced by earthquake loads perpendicular to the walls, could also be a factor triggering the formation of vertical cracks. Fig. 9 represents this type of failure, which was commonly observed in the village. This is also called "tensile failure." The main reason for the failure is the lack of a reliable connection between the vertical walls and horizontal elements (roof, floor, beam, lintel). Masonry structures with mortar joints lacking ductile components fail to perform adequately during earthquakes due to their inability to absorb and dissipate the energy from lateral inertial forces generated by earthquakes, leading to brittle failure of the walls (Liu et al. 2021).

Diagonal Shear Crack. Openings such as doors or windows in masonry infill panels have the potential to reduce the lateral strength and stiffness of infill-frame systems. Figs. 10(a–d) illustrate diagonal shear cracks in the masonry wall. Among these, buildings in Figs. 10(a, b, and d) have cracks originating from openings. The presence of openings hinders the transfer of loads, resulting in increased shear stress at lintel and sill levels, thereby causing the development of shear cracks. The expansion of openings within a wall contributes to a proportional increase in the stresses surrounding those specific openings (Shariq et al. 2008). Fig. 10(a) serves as a typical example of asymmetrically placed openings. This configuration consequently induced diagonal shear cracks. Fig. 10(c) depicts observed failures and cracks occurring at the corners, likely resulting from inadequate binding between the two lateral side walls and weak bonding in the corners.

Connection Failure of Walls. In Fig. 10(e), we can observe the failure between the walls attributed to inadequate bonding in the corner joint, resulting in their separation. Once this type of failure initiates, it will escalate the potential for collapse. An essential factor leading to these connection failures is the insufficient number of cornerstones. Other modern solution approaches include the use of proper reinforcement techniques like metal mesh or corner braces at the corners during construction.

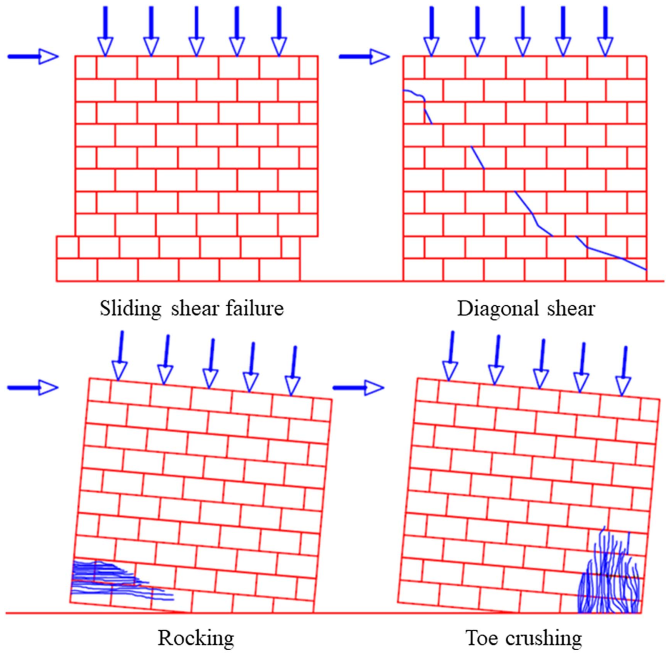

Fig. 8. Illustration showing common failure patterns of masonry walls subjected to in-plane shear.

Common Causes of Failures

Lack of Seismic Bands. Following the devastating 2015 Gorkha Earthquake, Nepal implemented building codes that mandate the inclusion of plinth bands, sill bands, lintel bands, gable bands, and dowel bands in load-bearing structures to allow proper load transfer during earthquakes. These bands can be made of either concrete or wood. However, residential structures in Jajarkot constructed before the 2015 earthquake completely lack these bands, leading to cracks propagating throughout the walls and resulting in the failure of the structure.

Even newly constructed buildings in Jajarkot, as depicted in Fig. 11(a), lack these essential bands, highlighting the lack of awareness and strict regulations. The presence of horizontal bands at different elevations in masonry walls helps resist the propagation of cracks and enhances bonding. However, the absence of these bands in Fig. 11(a) has led to the propagation of shear cracks in the corner, despite the wall being low in height, ultimately causing its collapse. On the other hand, in Fig. 11(b), the Jajarkot Palace, a remarkable architectural and historical monument having horizontal bands built 255 years ago, sustained only partial damage during the 2023 earthquake. The presence of bands has significantly contributed to its strength. Numerous historical monuments were destroyed during 2015 Gorkha Earthquake in Nepal as well, especially in Kathmandu Valley (Kawan et al. 2022). The use of wooden bands in its reconstruction has contributed to its increased safety. The incorporation of shear bands in masonry structures has been a longstanding practice in various countries for centuries and has demonstrated their effectiveness in improving the seismic performance of structures (Yadav et al. 2018). It is also promoted by the Government of Nepal in design manuals for rebuilding earthquake-resistant structures after the 2015 Gorkha Earthquake.

Aging of Masonry Materials. Many of the masonry structures in the Jajarkot area were constructed several generations ago, according to residents. These structures have never undergone strengthening or reconstruction since the occurrence of a major earthquake in Western Nepal centuries ago, specifically in 1505 AD. The mud mortar used in these buildings has deteriorated significantly, easily crumbling between one's fingers. This degradation serves as a clear indication that the mortar used in the buildings has aged to an extreme extent, including the Jajarkot Palace [Fig. 12(a)]. Similarly, field examinations have shown that many masonry buildings have walls made of randomly placed adobe bricks. Typically, they use mud mortar, lime, and cement as plaster materials. In these structures, the stress due to horizontal movement exceeds the decreased

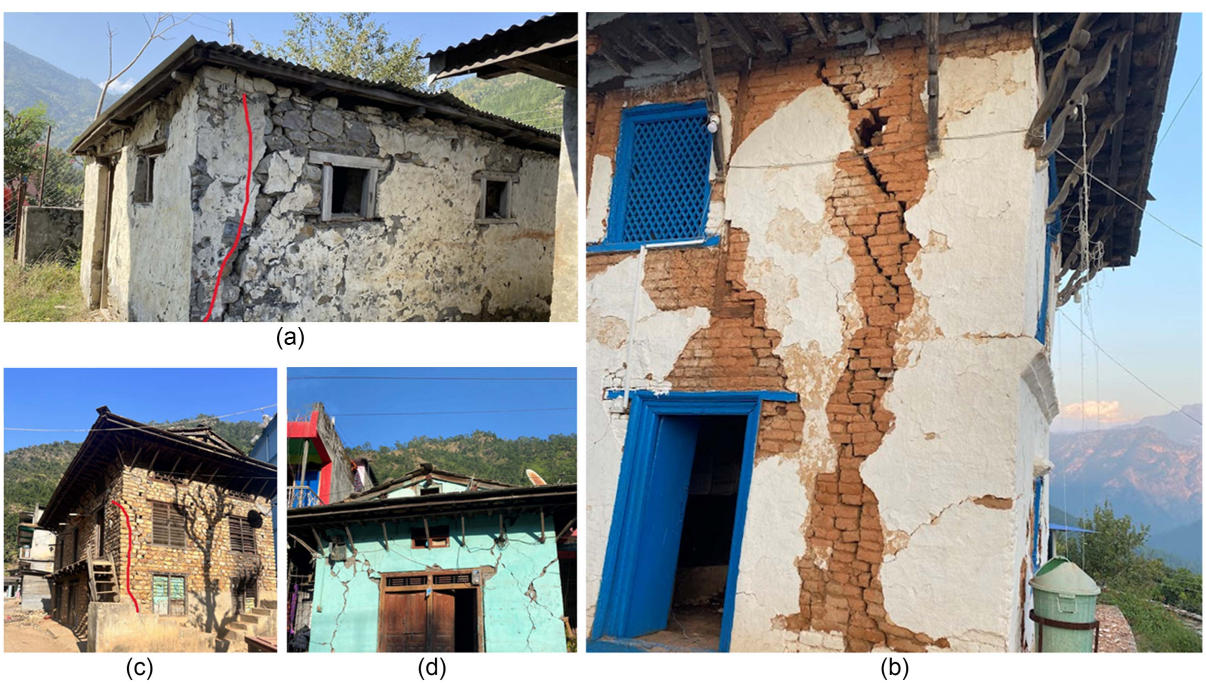

Fig. 9. Vertical shear crack: (a) masonry building; (b) Jajarkot palace; (c) three-story masonry building without bands; and (d) propagated at the wall of a building having both the opening at a shorter wall (28°41′56″ N, 82°12′01″ E). (Images by Rajan KC.)

Fig. 10. (a) Shear crack resulted from asymmetric arrangements of the window; (b) shear crack propagated throughout the wall (28°41′58″ N, 82°15′42″ E); (c) diagonal shear crack at masonry wall; (d) shear crack originated from openings spreading throughout the wall (28°41′57″ N, 82°16′44″ E); and (e) connection failure of walls due to lack of proper reinforcement and locking mechanism (28°41′35″ N, 82°14′03″ E). (Images by Rajan KC.)

Fig. 11. (a) Newly built building without bands in Jajarkot; and (b) less affected Jajarkot Palace with wooden bands (28°41′56″ N, 82°12′01″ E). (Images by Mandip Subedi.)

strength of aging materials leading to cracks and more damage [Fig. 12(b)].

Poor Workmanship. In rural areas of Nepal, including Jajarkot, people frequently hire local masons to construct their homes. These masons, without formal training, depend on visual assessments, hands-on experience, and guidance from more experienced individuals. Because of the absence of formal education and training in masonry in Nepal, many local construction projects are undertaken by these untrained masons, who rely on their own judgment. Buildings made of masonry were erected using either rounded or irregular-shaped stones arranged randomly [Fig. 13(a)]. The poor seismic performance of these structures was due to a lack of insufficient ties for the stones [complete collapse of the wall shown in Fig. 13(b)]. The mortar thickness in the affected areas appears to be excessively thick.

Heavy Roof. The roofs of the damaged buildings were typically constructed with a layer of stone spread over wooden planks. The aging of the layer of planks and wooden rafters led to a decrease in their load-bearing capacity, resulting in numerous roof failures during the earthquake (Fig. 14). Roof components built with wooden components having lower strength tend to deflect and sag, leading to water pooling in vulnerable areas. To avoid this, locals often opt to add a new layer of stone on top of an existing roof, thereby further increasing its load and hence increasing the risk of failure. In contrast, neighboring structures with roofs made of corrugated iron or other lighter materials experienced fewer failures.

Poor Connections between Walls and Roofs. The lack of sufficient connections between walls and roofs was noted as a contributing factor to increased damage. In most buildings, roofs were constructed with stone and timber directly placed on the load-bearing walls as

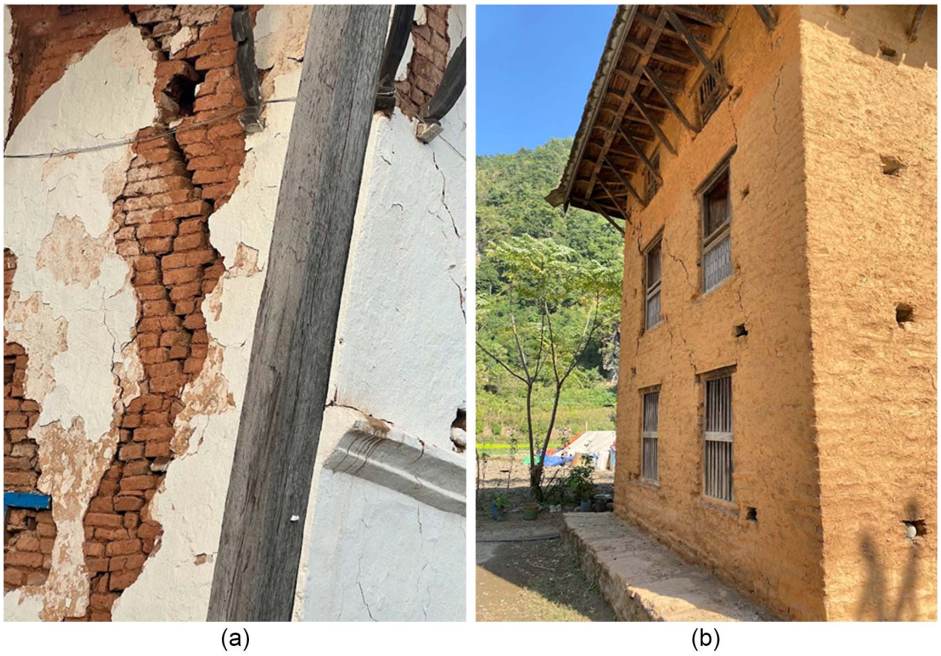

Fig. 12. (a) Extreme aged mortar resulting in lack of bonding between brick in Jajarkot Palace; and (b) aging of mortar resulted in cracks all around the building (28°41′56″ N, 82°12′01″ E). (Images by Rajan KC.)

Fig. 13. (a) Building made up of highly irregular and rounded stone; and (b) collapse building made up of boulder directly transported from river (28°41′55″ N, 82°13′45″ E). (Images by Rajan KC.)

Fig. 14. (a) High degree of weathering of the roof made by stone; and (b) collapse of stone roof resulting from deterioration of wooden support inside (28°41′56″ N, 82°12′01″ E). (Images by Rajan KC.)

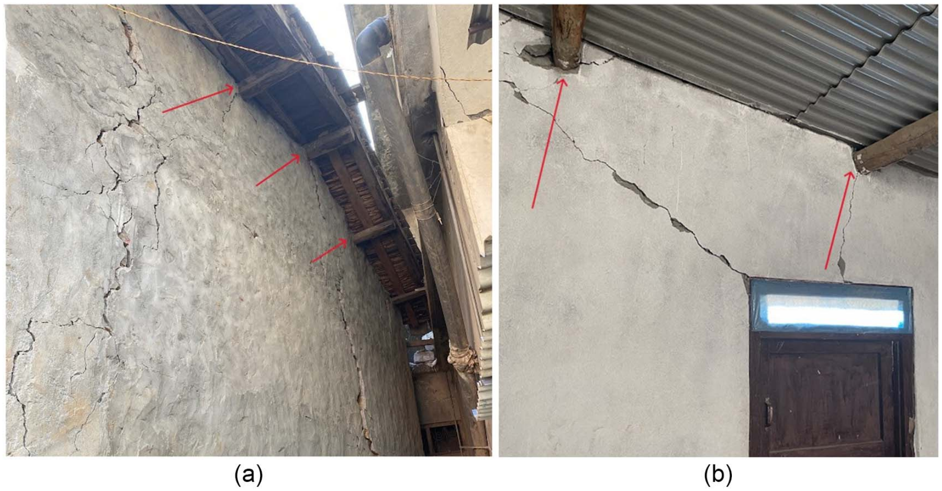

Fig. 15. Roof support resting on masonry directly and propagation of crack (28°41′55″ N, 82°16′46″ E). (Images by Mandip Subedi.)

shown in Fig. 15. As evidenced in the 2005 Kashmir Earthquake, walls supporting an inclined roof undergo lateral thrust in their out-of-plane directions, posing a serious risk of damage to the walls (Oyguc and Oyguc 2017). This scenario remained consistent following the 2023 earthquakes in Jajarkot, Nepal.

Damages to Reinforced Concrete Structures

The prevalence of reinforced concrete construction in the Jajarkot Earthquake-affected area is relatively low in comparison to masonry structures. Single- and two-story structures are common in RC construction, while high-rise buildings are relatively scarce. This low representation of RC buildings is influenced by factors such as local construction traditions, material availability, or economic considerations. The earthquake has not caused significant damage to the majority of RC structures, with the exception of some minor issues such as damage to infill walls and separation of columns from walls. This section presents some of the observed mechanisms of failure in RC at the affected site.

Strong Beam and Weak Column Connection

Significant damage was noted in an RC building equipped with rolling shutters, primarily linked to a column failure (Fig. 16 depicts its enlarged view). The installation procedure of rolling shutters requires the removal of the cover of RC columns at specific positions aligned with column. This exposes the primary reinforcement bars, which are then welded to the shutter guide. The incorporation of rolling shutters significantly altered the stiffness and moment capacities of the RC columns by decreasing the column's cross-sectional area and reducing the strength and stiffness of the reinforcement bars resulted from overheating caused by the welding procedures. Similar findings were noted in the aftermath of the 2015 Gorkha Earthquake in Nepal (Sharma et al. 2016), and the Koceali Turkey 1999 earthquake (Sezen et al. 2003).

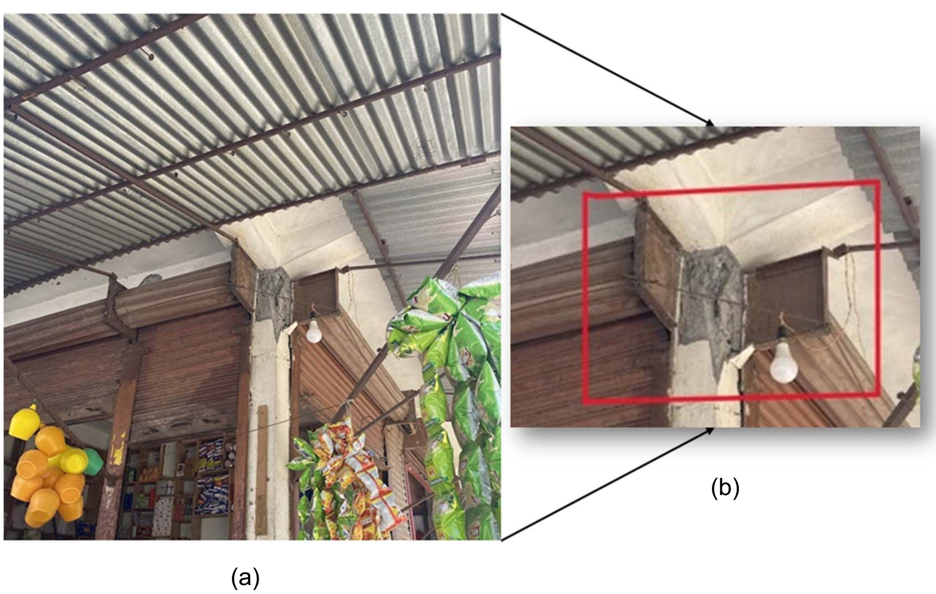

Fig. 16. (a) Destructed column due to the installation of rolling shutter at Rimna Bazaar, Jajarkot; and (b) enlarged view (28°41′55″ N, 82°16′46″ E). (Images by Rajan KC.)

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(a) (b)

Fig. 17. Crushed RC wall and column made up of poor concrete mixture with elongated aggregate (28°41′55″ N, 82°13′45″ E). (Images by Rajan KC.)

Strong beams and weak columns in a house can lead to catastrophic failure during earthquakes. Columns support vertical and lateral loads and may buckle or collapse first, causing a progressive structural failure. To ensure stability and integrity, columns must be stronger than beams to safely transfer loads and withstand stress. During an earthquake, lateral forces affect the structure. While strong beams can handle these forces, weak columns may deform or collapse, weakening seismic resilience and possibly causing a "soft story" collapse, where one level fails, leading to the collapse of levels above. Modern design codes, like the IBC and Eurocodes, stress the "strong column, weak beam" principle to ensure failures are ductile (gradual and energy-absorbing) rather than brittle (sudden and catastrophic). This approach maintains structural integrity and provides time for occupants to evacuate during extreme events. During an earthquake, lateral forces can challenge the structure. While strong beams can withstand these forces, weak columns may fail, leading to a "soft story" collapse. Modern design codes, such as the IBC and Eurocodes, prioritize the "strong column, weak beam" approach to ensure failures are ductile and energy-absorbing, preserving structural integrity and providing time for evacuation.

Poor Quality of Concrete

It was evident that inferior concrete quality was used to construct the buildings damaged during the earthquake. Low-strength concrete utilized in RC structures are illustrated in Fig. 17. The concrete in these structures readily crumbled when touched by hand, signifying a notable decrease in its strength. The substantial weakening of concrete materials resulted from the use of large and poorly graded aggregates, resulting in a honeycomb pattern in the cast concrete, further weakening its strength. The spalling of concrete in numerous RC buildings during the Haiti Earthquake of 2010 was attributed to subpar concrete quality and defects in workmanship as well (Rathje et al. 2011; O'Brien et al. 2011).

Destruction of the Infilled Wall

Due to the absence of sufficient connection measures between the infill wall and the beam-column in the frame structure construction, infill walls are prone to detachment at their interface, resulting in a penetration crack, as illustrated in Fig. 18. Infill wall destruction and diagonal shear crack in RC buildings was also a common mode of failure in previous earthquakes like the 2001 Bhuj Earthquake in India (Goel 2001).

(a) (b)

Fig. 18. Destruction of infill wall of four-story RC house at Rimna Bazaar, Jajarkot (28°41′55″ N, 82°16′46″ E). (Images by Rajan KC.)

(a) (b)

Fig. 19. (a) Undersized column; and (b) all rebars cut in the same level (28°41′55″ N, 82°13′45″ E). (Images by Mandip Subedi.)

Construction Practice and Compliance with Code

Most of the damaged structures in the area were constructed using brittle masonry and poorly designed and constructed reinforced concrete. Numerous houses were constructed by their owners, aided by local masons who are unfamiliar with the Nepal Building Code (NBC) and solely rely on their own construction expertise. As a result, the houses were built without engineering consultation and proper specifications, making them more susceptible to damage. Notably, the column size in these buildings is 9×9 in. [Fig. 19(a)], falling below the minimum size recommended by NBC, which is 12×12 in. Another concern is the inadequacy of vertical reinforcement. In some cases, columns in two- and three-story buildings contain only four 12 mm diameter rebars, with lateral ties spaced more than 300 mm apart. Additionally, a common practice is joining all rebars at a single joint with a much shorter splice length [Fig. 19(b)].

In Jajarkot and West Rukum, masonry structures, old and newly constructed, failed to adhere to building codes and essential guidelines. However, after the 2015 Gorkha Earthquake, structures in the 14 districts significantly impacted, excluding those areas affected by the Jajarkot Earthquake, were rebuilt in accordance with established building regulations. This adherence followed the guidelines set forth in the NBC, a practice that must be obligatory for reconstructions in the regions affected by the 2023 Jajarkot Earthquake in Nepal and across Nepal to guarantee structural safety and resilience.

Strict adherence to building codes can markedly decrease earthquake-related casualties. Despite the mandatory compliance, municipalities face challenges in regulating permits and inspections due to insufficient mechanisms and resources. After the 2015 Gorkha Earthquake, the Government of Nepal made it mandatory to comply with building code: NBC 105 to receive a reconstruction grant (approximately \$2300 for the construction of each building). However, due to the lack of availability of expert engineers, many homeowners built their houses according to their style and requirements, without following the mandatory rule of thumb. A case study in Dhading District carried out by Shrestha et al. (2021) revealed that, out of a total of 53,109 reconstructed house, 4.01% of buildings were built without following the minimum code requirements.

Practical Applications

The seismic performance of buildings during the November 3, 2023, Jajarkot Earthquake in Nepal offers critical insights for improving building resilience. One of the primary findings was the significant impact of weak connections between floors and walls in masonry structures. Strengthening these connections with anchor ties or reinforced ring beams can significantly enhance structural integrity. Additionally, the implementation of seismic bands at different levels, using through cornerstones, and replacing gable walls with lightweight materials like wood planks or steel sheets, can substantially reduce damage. Modern reinforcement techniques, such as using metal mesh or corner braces, are also recommended to improve the durability of masonry buildings.

For RC buildings, the study identified that poor seismic performance often resulted from inferior construction materials and poor workmanship. Ensuring the use of high-quality materials and skilled labor is crucial to enhancing building resilience. Many RC buildings were found to contain substandard concrete or low-strength handmade bricks, highlighting the need for adherence to material standards and regular inspections to prevent such deficiencies.

On the policy and implementation front, the strict enforcement of building codes, such as those outlined in the Nepal NBC, is essential. These codes need to be updated and tailored to the specific conditions in Nepal to ensure their effectiveness. Developing targeted retrofitting programs for existing buildings can address current vulnerabilities, including public infrastructure and private homes. By implementing these measures, the risk of extensive damage and loss of life in future earthquakes can be significantly reduced. Our study provides a roadmap for local governments and policymakers to enhance building resilience, ultimately contributing to safer communities in seismic regions.

Conclusion

The 2023 Jajarkot Earthquake in Nepal recorded a peak ground acceleration (PGA) up to 70 cm/s^2, which is significantly below the projected PGA range (295–340 cm/s^2) with a 10% chance of occurrence within a 50 year timeframe. Despite this lower PGA, significant structural damage occurred in the broader epicenter region. This indicates that, if the PGA had been higher, all villages near the epicenter would have faced extreme devastation.

This study explores the structural damage in masonry and reinforced concrete buildings resulting from the earthquake. By summarizing various types of damage and analyzing their possible failure mechanisms, the study provides insights that can aid in retrofitting existing buildings and strengthening building codes. The prolonged seismic gap of more than five centuries in Western Nepal has led to significant energy accumulation, which could result in a major to mega-scale earthquake at any moment. In this regard, the November 3, 2023, Jajarkot Earthquake in Nepal provides a critical opportunity to assess the resilience of existing structures, undertake retrofitting measures, and ensure compliance with structural codes in future construction projects.

The NBC, based on the Indian Standard Code of Practice, requires amendments to align it with the specific conditions and requirements of Nepal. The majority of the structures consist of stone masonry; however, only minimal research has been conducted to analyze the performance of stone masonry under seismic activity.

The seismic performance of buildings during the Jajarkot Earthquake revealed that, for masonry structures, weak connections between floors and walls likely caused numerous out-of-plane failures. These failures can be prevented by using anchor ties or reinforced ring beams. Additionally, implementing seismic bands at different levels, through cornerstones, and replacing gable walls with lightweight materials like wood planks or steel sheets can significantly reduce earthquake damage. Modern reinforcement techniques during construction, such as metal mesh or corner braces, also play a crucial role. For reinforced concrete buildings, poor seismic performance often results from inferior construction materials and poor workmanship. Many severely damaged RC buildings contained substandard concrete or low-strength handmade bricks with thick mortar joints. It is crucial to use high-quality materials and skilled labor in all building construction to ensure seismic resilience. This research offers a comprehensive plan for enhancing the seismic resistance of structures in Western Nepal. By incorporating these suggestions, upcoming development projects may be more effectively prepared to endure seismic disasters, ultimately leading to the creation of safer and more resilient societies.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Author Contributions

Rajan KC: Data curation; Formal analysis; Investigation; Methodology; Software; Writing–original draft. Kabin Lamichhane: Formal analysis; Software; Visualization; Writing–original draft. Keshab Sharma: Conceptualization; Methodology; Supervision; Validation; Writing–review and editing. Mandip Subedi: Conceptualization; Investigation; Project administration; Resources; Supervision; Writing–review and editing. Shikshita Bhandari: Formal analysis; Methodology; Software; Validation; Writing–review and editing.

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