Performance Assessment of Buildings Impacted by the 2019 Windstorm in the Central-South of Nepal

Apil KC[1]; Keshab Sharma, Ph.D.[2]; Rajan KC[3]; Kabin Lamichhane, Aff.M.ASCE[4]; and Mandip Subedi[5]

Abstract: The 2019 windstorm in Nepal struck villages in the Bara and Parsa districts, central-south of Nepal, on March 31, 2019, causing widespread devastation. The storm, rated five (5) on the Enhanced Fujita Scale, cut a 33 km swath through central-southern Nepal. In total, 1,452 private houses were destroyed, while 1,373 others suffered partial damage. The tragic storm claimed 28 lives and left 1,155 individuals injured. The impact of this tragedy extended to nearly 3,000 families. Immediately after the storm, a comprehensive damage assessment framework was developed, and a field reconnaissance study was conducted to understand the damage distribution and building failure mechanisms under tornado wind loads. Common damage modes observed were roofing material damage, roof-to-wall connection failure, and brittle masonry wall failures in the affected areas. This paper presents the lessons learned from damage to the building infrastructure during the 2019 windstorm in Nepal. Examined buildings underscore the critical need for design alternatives and sustainable retrofits, emphasizing load path integration and strong roof-to-wall connection. Strengthening the building envelope can significantly enhance its resilience against storms and other disasters prominent in the region. This study highlights the importance of proactive measures to safeguard vulnerable communities against natural hazards and offers insights into resilient building construction technology. **DOI: 10.1061/JPCFEV.CFENG-4846.**

Author keywords: Windstorm; Field reconnaissance; Damage assessment; Building performance; Roof damage; Nepal.

Introduction

Windstorms including cyclones and hurricanes wreak significant havoc in various regions worldwide, leading to loss of life and property, as well as extensive damage to residential homes, industrial buildings, power transmission lines, communication towers, and other structures (Mendelsohn et al. 2012; Messmer and Simmonds 2021; Shanmugasundaram et al. 2000; Shultz et al. 2005; Taillie et al. 2020). On March 31, 2019, a windstorm in the central-south districts of Nepal, Bara and Parsa, killed 28 individuals, injured a total of 1,155 individuals, obliterated 1,452 private houses, and damaged 1,373 houses partially, affecting a total of 2,825 families (DRR Portal 2020). The windstorm persisted for approximately 45 min, impacting an extensive area spanning 33 km in width and extending up to 45 km in length (Pokharel 2022). The storm itself was the first case of similar disasters in Nepal. The windstorms overturned vehicles, uprooted trees, and brought down power lines in the affected areas. Details are shown in Fig. 1.

In windstorm-affected areas, the prevalent building construction types include adobe and brick masonry walls, constructed with dry or mud or cement mortar, with roofs made of pitch thatch or mud tile or galvanized iron sheet. The seismic performance of these buildings in past earthquakes was observed to be quite poor (Gautam and Chaulagain 2016; Sharma et al. 2016). Further, such buildings are the most vulnerable to lateral loads such as earthquakes and strong winds, where roofs are particularly vulnerable when subjected to moderate to severe wind intensity. Nepal, a low-income country experiencing rapid urbanization (Karki et al. 2024), employs various affordable and durable roofing materials in its rural areas, including those affected by the 2019 windstorm. These materials include timber, bamboo, wooden shingles, corrugated galvanized iron (CGI) sheets, tiles, and thatch. Despite their widespread adoption, there needs to be more understanding of the effects of wind on these materials, and there is a dearth of studies on their impact on structural details and configurations. Lotay (2015) studied windstorm damage to rural home roofs in Bhutan during 2011 and 2013, comparing them to Japanese roofs. This study found failures due to poor connections and inadequate timber during strong winds. Alam et al. (2017) found that buildings in cyclone-prone areas of Bangladesh, constructed with local materials (mud, bamboo, straws, tiles, wood, jute sticks, bricks, and CGI sheets), were structurally unstable or too weak to withstand high-speed winds. Mukhopadhyay and Dutta (2018) identified sloped roof structures and masonry wall junctions as the primary points of failure in cyclone-prone regions of the Indian subcontinent. Following the 2019 windstorm in Nepal, Gautam et al. (2020) attributed roof failure to insufficient anchorage between the roof and the structural system. Chettri et al. (2022) discovered that roof components, including cladding, sheathing, and trusses, are highly susceptible to damage from wind uplift pressure.

In Nepal, premonsoon windstorms, usually occurring between April and May, can cause damage to poorly connected roofs (Mäkelä et al. 2014), but they rarely reach intensities, leading to significant

[1]Ph.D. Student, Taubman College of Architecture and Urban Planning, Univ. of Michigan, 2000 Bonisteel Blvd., Ann Arbor, MI 48109. ORCID: https://orcid.org/0000-0001-9313-040X. Email: apil@umich.edu

[2]Geotechnical Engineer, BGC Engineering Inc., 330 Alison Blvd., Fredericton, NB, Canada E3C 0A9 (corresponding author). Email: ksharma@bgcengineering.ca

[3]Geotechnical Engineer, Geoinfra Research Institute, Chakupat, Lalitpur-11 44600, Nepal. ORCID: https://orcid.org/0000-0001-8471-6361. Email: rajankc.ioe@gmail.com

[4]Undergraduate Student, Dept. of Civil Engineering, Tribhuvan Univ., Thapathali Campus, Kathmandu 44600, Nepal. ORCID: https://orcid.org/0009-0003-3276-7708. Email: kabin.762416@thc.tu.edu.np

[5]Associate Professor, Dept. of Civil Engineering, Universal Engineering and Science College, Chakupat, Lalitpur-11 44600, Nepal. Email: mandip.subedi@gmail.com

Note. This manuscript was submitted on March 20, 2024; approved on July 10, 2024; published online on October 17, 2024. Discussion period open until March 17, 2025; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Performance of Constructed Facilities***, © ASCE, ISSN 0887-3828.

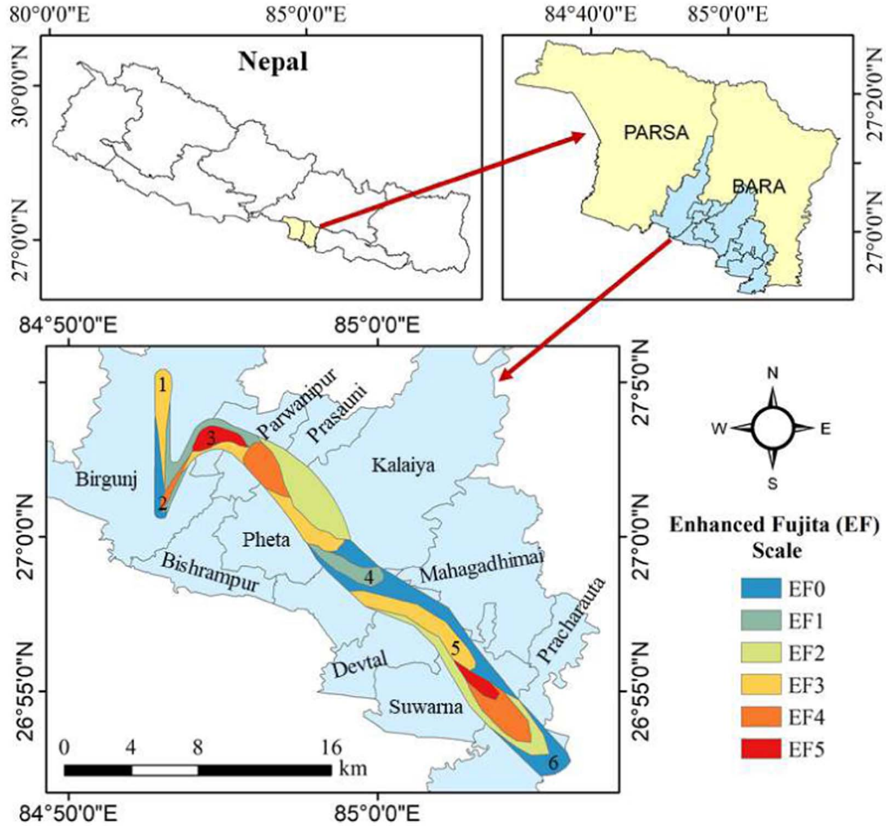

Fig. 1. Location map showing path of central-south windstorm with proposed local intensity derived from damage observations during reconnaissance (affected areas: 1 = Jagannathpur; 2 = Ghantaghar; 3 = Lipanimal; 4 = Dharmanagar; 5 = Telgai; and 6 = Bairiya).

casualties. Meanwhile, hurricanes, commonly known as cyclones or typhoons depending on the region, are tropical storms that usually develop over warm ocean waters (Oey et al. 2007; Shay et al. 1992), Nepal's geographic positioning as a landlocked and mountainous nation makes it a rare case for such storms, where we undertake that wind-induced damage to buildings and structures is uncommon in the country (Gautam et al. 2020). However, due to its geological and topographical features, the region is more prone to other natural disasters such as landslides, avalanches, and earthquakes (Meena et al. 2019; Nadim et al. 2006). Unlike the common acceptance, the devastation in central-southern Nepal on March 31, 2019, marks one of the worst disaster events caused by a windstorm in modern Nepalese history, underscoring the necessity for comprehensive research and consideration of wind disasters in infrastructure design, primarily in residential buildings.

The frequency, intensity, and duration of extreme weather and climate events, such as windstorms, are increasing due to climate change around the globe including in Nepal (Chapagain 2024). But, the behavior of residential buildings in South Asia, including Nepal, Bhutan, India, and Afghanistan, which are highly vulnerable to hydro-meteorological and geological hazards, when subjected to major storms, must be better understood and investigated (Kafle 2017). Studying wind damage patterns to residential buildings in the high Himalayan regions, characterized by unique weather patterns and topography, is essential due to the significant risks posed by high winds. Understanding wind damage here can inform the development of tailored building codes, enhancing resilience against these challenges.

Postdisaster reconnaissance studies are crucial for understanding the impact on built infrastructure and communities (Lozano and Tien 2023; KC et al. 2024; Khajwal and Noshadravan 2024). They assist urban planners, stakeholders, and government entities in making informed decisions to enhance community resilience, exposing the vulnerable practices and limitations caused due to socioeconomic conditions. Key aspects include assessing the disaster impact on infrastructure, categorizing vulnerable components, and informing decisions on code updates, sustainable retrofit solutions, emergency response practices, and preparedness for future disasters (Subedi et al. 2024; Sharma et al. 2018; Masoomi et al. 2018). This postdisaster reconnaissance study evaluates residential building performance in central-southern Nepal during the 2019 windstorm, offering insights into wind speed experienced based on the Enhanced Fujita scale. The storm path shown in Fig. 1 was developed based on the reported damage and local informants. Common failures observed include the total collapse of roofing systems in many residences and semiengineered buildings with thatch, tiles, corrugated galvanized iron (CGI) sheets, slabs, connection failures, gable wall failures, and wall failures. This paper showcases, through photographs, the damage inflicted on various structures. It also offers recommendations to enhance the resistance of different structures against windstorms.

Estimation of Wind Speed

Nepal possesses equipment for rain forecasting and has recently implemented lightning forecast systems. However, it lacks adequate resources to measure wind speed. The Department of Hydrology and Meteorology (DHM) predicted the windstorm's average speed was 55–75 km/h (Rimal 2019). However, wind speed was estimated indirectly using the Enhanced Fujita (EF) scale on peak-damaged areas, which provides a correlation between observed

Table 1. Enhanced Fujita damaged intensity scale and damage description

Category	Wind speed	Damage description
EF0	105–137 km/h	Minor damage Some damage to TV antenna and chimneys, tree branches broken, and shallow-rooted trees toppled.
EF1	138–177 km/h	Moderate damage Small area of roof blown off, small trees uprooted, occasional car flip, and stripped corn stalks, with doors, siding, and sheds blown away.
EF2	178–218 km/h	Strong damage Whole roof ripped off, uprooted trees, overturned cars, and complete collapse of weak structure.
EF3	219–266 km/h	Severe damage Blown away of roofs and walls, trees uprooted. High-rises lose windows, industrial buildings damaged, and large vehicles are displaced several meters.
EF4	267–322 km/h	Devastating damage Trees partially stripped, cars tossed, homes destroyed, trains derailed, barns leveled, and high-rises significantly damaged in a destructive event.
EF5	>322 km/h	Incredible damage Most buildings are demolished, cars thrown yards away. Homes and businesses swept, trees debarked, corn flattened, skyscrapers damaged, debris poses danger.

Source: Data from McDonald et al. (2010).

damage and wind speed. The windstorm on March 31 in Nepal can be categorized as an EF4 storm based on the Enhanced Fujita scale, corresponding to wind speeds between 267 and 322 km/h. Uprooted or snapped large trees and trucks lifted off the ground were observed at many places, which can justify the occurrence of an EF4-level storm in central-southern Nepal. Based on the field observations, the Fujita scale indicates the windstorm was a tornado. DHM claimed that the destructive storm on March 31 had similar character to a tornado. Further details of the EF Scale are presented in Table 1.

The reconnaissance team collected evidence of the wind speed using the phenomena explained in the tornado intensity scale established by Fujita and Pearson. The reconnaissance team after careful observation concluded that this tornado had a Fujita Intensity of F1 with some localities experiencing an intensity of F2. The wind speeds corresponding to two intensities are 140 and 180 km/h, respectively. The DHM states that despite the forecasted average windstorm speed ranging from 55 to 75 km/h, the actual damages in localized areas are considerably higher. Meanwhile, the phenomena that were observed for wind speed include the degree of damage to residential buildings, electric poles, trees, and blown-up vehicles.

Building and Roof Types

In the 2021 National Population and Housing Census, Nepal, recorded a population of 29,164,578 distributed among 6,666,937 distinct households. Notably, mud-bonded brick/stone masonry structures emerged as the most prevalent type across all regions, comprising 30.67% of all structures, with bamboo buildings accounting for 11.71%. In contrast, urban areas such as Kathmandu Metropolitan City displayed a predominance of cement-bonded brick and stone structures (29.79%) and cement concrete structures (28.94%). The central-southern region of Nepal, also recognized as Madhesh province, features foundations predominantly made of wooden or bamboo pillars, constituting 38.20% of the structures. This typology is particularly susceptible to windstorm damage. Table 2 shows the total number of buildings and their roofing material details of the different local levels of the Bara district that are affected by the 2019 central-south windstorm. Tile roofs, galvanized sheet roofs, and reinforced cement concrete roofs are prevalent in these areas.

Adobe buildings [Fig. 2(a)] are commonly found in rural Nepalese communities. Adobe buildings are also nonengineered constructions prevalent in many suburbs and villages in Nepal. The structural integrity of building elements is weak in adobe houses due to poor binding and nonhomogenous construction. Wooden buildings [Fig. 2(b)] are prevalent in proximity to forested areas, featuring wooden posts from tree trunks and walls made of wooden planks or woven bamboo with mud plastering. In Nepal, masonry buildings [Fig. 2(c)] typically consist of sun-dried/burnt bricks or stone walls with mud mortar and a wooden building frame. In urban settings, brick or stone buildings are constructed

Table 2. Number of households by type of materials used for roof of housing unit in wind affected area of Bara district

Local levels	Total buildings	Galvanized sheet	Reinforced cement concrete	Thatch/straw	Tile	Stone/Slate	Wood planks
Devtal rural municipality	3,977	562	1,249	584	1,545	21	16
Mahagadhimai municipality	9,757	601	3,800	903	4,308	62	83
Pacharauta municipality	6,161	668	1,853	753	2,730	132	25
Parawanipur rural municipality	3,964	535	2,400	276	718	27	8
Pheta rural municipality	4,196	566	1,896	640	983	102	9
Prasauni rural municipality	3,966	415	2,077	523	929	13	9
Subarna rural municipality	5,049	379	1,620	608	2,426	8	8

Source: Data from Census (2021).

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

Table 3. Brief description of building typologies in study area

Building type	Description	Figure reference
Adobe	Constructed from a mixture of mud, water, cow dung, and organic materials, with or without a wooden frame; these materials typically have a wall thickness ranging from 200 to 350 mm and lack any reinforcement. Such structures are highly susceptible to both wind and earthquakes.	Fig. 2(a)
Wooden	Built with wooden posts sourced from tree trunks and walls constructed from wooden planks or woven bamboo with mud plastering; bamboo posts are inserted into the ground up to approximately 1 m. The walls lack reinforcement, making the structure susceptible to wind, earthquakes, and fire.	Fig. 2(b)
Brick in mud mortar	Unreinforced brick masonry in mud mortar, without confinement, featuring wood or masonry lintels and wood-framed floors supporting substantial mud floor and roof slabs, with half brick wall thickness of around 110 mm, is particularly susceptible to both wind and earthquakes.	Fig. 2(c)
Brick in cement mortar	Residential buildings of low height, constructed with burnt bricks using cement mortar, may or may not include light reinforcement. The outer wall has a thickness of 230 mm, while the inner wall is 115 mm thick, rendering them susceptible to both wind and earthquakes.	Fig. 2(d)
Non-engineered RC	Reinforced concrete frames with brick infills, lacking structural design compliance with building codes. The structure features cast-in-place concrete beams and columns, along with cast-in-place concrete slabs for floors and/or roof. The inadequacy in providing sufficient wind load and seismic resistance makes the structure vulnerable.	Fig. 2(e)
Engineered RC	Reinforced concrete frames with brick infills, incorporating cast-in-place concrete beams and columns along with concrete slabs, typically adhere to Nepal building codes and Indian standard codes for seismic design. Special detailing is implemented to ensure ductile performance, rendering the structure relatively safe.	Fig. 2(f)

with cement mortar, incorporating or omitting limited reinforcement [Fig. 2(d)]. Reinforced concrete (RC) moment-resisting frame structures [Figs. 2(e and f)] have become the predominant construction type in public and commercial buildings since the 1988 Udayapur earthquake. Pre-1988, most RC buildings were nonengineered, lacking proper seismic resistance as structural engineers did not design them. The newer engineered RC buildings [Fig. 2(f)] often adhere to Nepal building codes and Indian standard codes for seismic provisions. Table 3 presents a brief description of different typologies.

Table 4 presents the roof types and their brief description. Residential structures in the affected areas were typically wood-frame single-family dwellings with pitched roofs. The most prevalent roof covering for residential structures was asphalt shingles. Other roof coverings, seen occasionally, included metal (standing seam and through panel attached), clay tile, fiber-reinforced cement shingles,

Table 4. Brief description of roofing typologies in study area

Roof type	Description
Thatch	Constructed from grass, wheat, or maize straws with split bamboo framing, featuring a double-pitched roof that rests on walls without proper connection or with weak connections to wooden or bamboo posts; these structures are highly susceptible to wind and fire hazards.
Mud tile	Crafted from clay and shaped on a potter's wheel into cone shapes, these baked clay tiles are halved and then fired in a kiln. They are positioned on the scantling of bullies made of secondary wood and secured with split bamboo battens.
CGI sheet	Commonly employed in the construction of masonry and reinforced concrete buildings by middle-class families, purlins are made from materials such as steel tubes, bamboo, or wood.
RC slab	Concrete slabs cast in place, with a thickness ranging from 75 to 100 mm, exhibit reduced susceptibility to both wind loads and fire.
Asbestos	Fibrous cement sheets, steel tube, bamboo, or wood are used as purlins
Plastic	Utilized by those with limited means, plastic serves as a roofing material supported by split bamboo framing. It is less resilient and particularly susceptible to both wind and fire hazards.

and wood shakes. Exterior wall cladding was predominantly wood siding on older houses and brick veneer or a combination of brick veneer and siding boards (wood, vinyl, or aluminum) on newer homes. Madhesh province, encompassing the windstorm-affected districts of Bara and Parsa, exhibits a diverse roofing composition, with 37.4% being tile roofs, 35.2% reinforced cement concrete (RCC) roofs, 19.2% galvanized sheet roofs, and 7.2% thatch/straw roofs, according to the 2021 census. Thatch/straw, galvanized sheet, and tile roofs are prevalent in the rural areas of this region. These roofing types are particularly vulnerable to damage during this disaster.

Nevertheless, Nepal currently needs comprehensive codes specifically dedicated to wind load. The existing wind load code is the NBC 104: 1994, which is largely inspired by the "Indian Standard IS:875 (Part 3) 1987—A code of practice for design loads (excluding earthquake) for buildings and structures (second revision)." It is crucial to amend NBC 104: 1994 to align with Nepal's geographical conditions for optimal implementation, also considering the building typologies in Nepalese context. In Nepal, building codes neglect essential considerations such as lateral and wind loads in high-rise structures. This oversight and a lack of awareness regarding roof-to-wall connections jeopardize safety and structural integrity. Urgent attention is needed to rectify these gaps and ensure buildings adhere to international safety standards. Events such as the 2019 central-south windstorm reconnaissance can offer valuable insights. This oversight poses significant structural integrity and safety risks, potentially endangering occupants, and neighboring structures, also when such implications are ignored in high-rise construction as well. Furthermore, the lack of emphasis on roof-to-wall connections in building technology awareness further exacerbates these vulnerabilities. The authorities and industry professionals must address these shortcomings promptly, ensuring building designs prioritize resilience against natural forces and adhere to internationally recognized safety standards.

Damage Assessment of Buildings

An immediate survey was conducted after the central-south windstorm in Bara and Parsa. Comprehensive data for 327 significantly impacted residences were gathered, including parameters such as dimensions, architectural typologies, roof configurations, and specific failure characteristics. One of the authors conducted on-site visits spanning six days to collect detailed information meticulously. The comprehensive observation site encompasses wards 1, 2, 3, 6, and 7 of Pheta Rural Municipality (Pheta RM), Bara, shown in Fig. 3. The study also gathered comprehensive information on fatalities, injuries, and failure categorizations throughout the affected area in Bara and Parsa. The findings, mapped in Fig. 1, provide insights into the windstorm's trajectory and local intensity highlighting the spatial distribution of the damage interpreted using the EF scale. Fig. 1 shows that the damage zone spans approximately 2.2 km in width and 42 km in length. The path of windstorm starts in Jagannathpur and ends in Bairiya, with visible turning points Lipanimal, Dharmanagar, and Telgai. In-depth details of building damage and human losses within the affected areas based on 327 sample data are provided in Table 5. Higher EF ratings were observed in the densely populated areas and regions with vulnerable buildings.

Analyzing the 327 data points, prevalent building types in the windstorm-affected community include brick with cement mortar (33.64%), wooden structures (31.19%), brick with mud mortar (22.32%), and adobe constructions (12.84%) as illustrated in Fig. 4(a). Among these building typologies, dominant roof types consist of mud tiles (54.43%), thatched roofs (20.18%), plastic roofs (14.98%), asbestos sheets (5.20%), CGI sheets (3.98%), and RC slabs (1.22%), as depicted in Fig. 4(b). The graphical representation of the association between roof types and different building typologies is presented in Fig. 4(c).

After analyzing building types and roof associations, we observed two main failure patterns: roof failure alone and combined roof and building failure, which can be partial or complete, as detailed in Table 6. Our findings indicate that Adobe buildings predominantly experience building failure, regardless of roof type, a trend similar to that observed in wooden buildings. For brick buildings with mud mortar, roof failure is prominent in thatched, plastic, and asbestos sheet roofs. In brick buildings with cement mortar, roof failure is more common than building failure, except in mud tiles and RC slab roofs. The weight of the latter two roofs might cause a lower incidence of failure.

This section investigates damage to diverse building and roof typologies, detailing potential causes. It addresses both structural and nonstructural vulnerabilities. High winds damaged adobe and unreinforced masonry walls, posing a risk to older buildings and specific metal structures. Additionally, various roofing types and rooftop equipment suffered damage. Residential roof coverings experienced significant blow-offs, damaging residential structures from fallen trees. Postwindstorm assessments revealed three primary types of roof damage: (1) roofing material damage; (2) roof-to-wall connection failure; and (3) support string failure. Observations also noted a relatively lower occurrence of both structural and nonstructural member failures in reinforced concrete buildings.

J. Perform. Constr. Facil., 2025, 39(1): 04024052

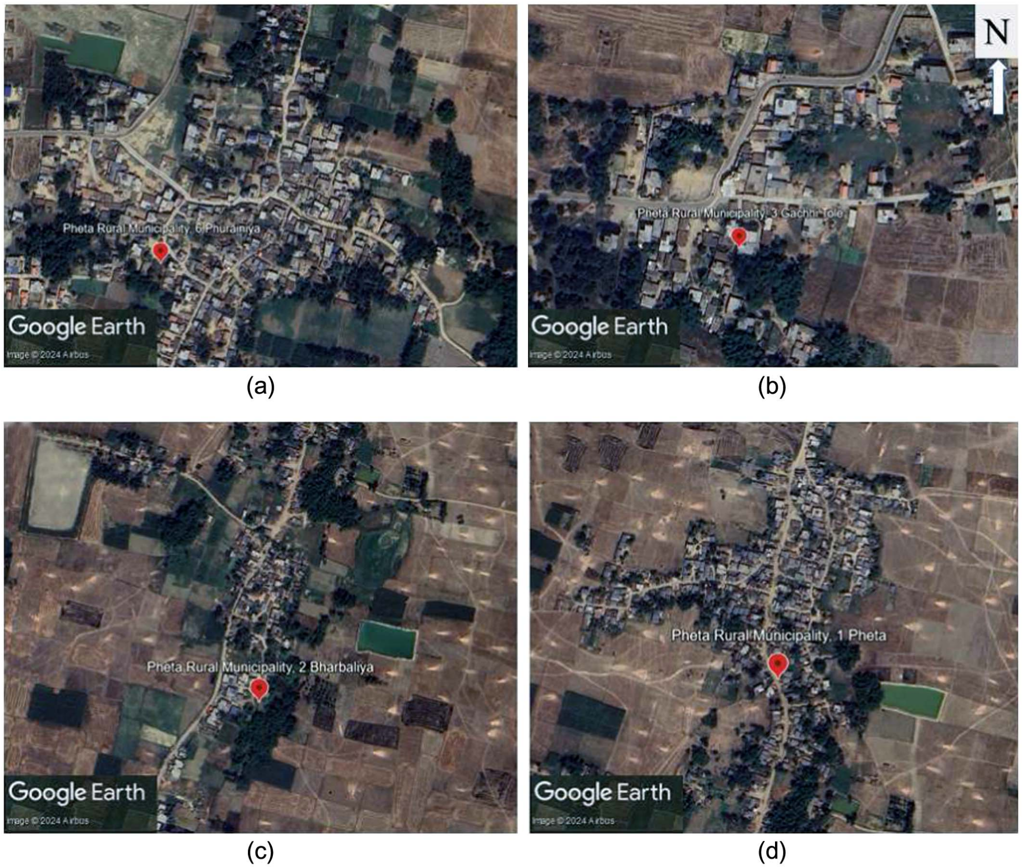

Fig. 3. Detailed observed sites: (a) Pheta RM, 6 Phurainiya; (b) Pheta RM, 3 Gachhi Tole; (c) Pheta RM, 2 Bharbaliya; and (d) Pheta RM, 1 Pheta, following central-south windstorm of 2019. (Image © Google, Image ©2024 Airbus.)

A similar pattern emerged during Hurricane Katrina along the Mississippi Gulf Coast, where reinforced concrete, steel frame, and heavy timber structures demonstrated strong resilience, experiencing minimal structural damage (Eamon et al. 2007).

Table 5. Details of building damage and human losses in the affected area

Location	Completely damaged house	Partially damaged house	Death count	Injury count	Remarks
Birgunj–8	200	0	0	0	
Birgunj–22	118	0	0	0	
Parwanipur–4	300	248	1	0	
Prasauni–4	60	115	1	0	
Prasauni–6	8	11	0	0	
Kalaiya–18	24	6	1	0	
Kalaiya–12	1	9	4	15	Damaged brick industries
Devtal–7	40	85	0	0	
Mahagadhimai–7	29	57	1	0	
Suwarna–8	75	45	1	0	
Suwarna–5	34	82	1	0	
Suwarna–4	38	27	0	0	
Suwarna–1	62	19	0	0	
Pachaurata–2	8	3	0	0	
Pachaurata - 7	16	152	0	0	
Pheta–7	9	6	0	0	Damaged 1 healthpost
Pheta–6	55	23	12	0	
Pheta–1	130	60	6	0	Damaged 1 brick industries

Damage Chain of Roof

Roof damage in a windstorm follows a sequential process, as illustrated in Fig. 5. The windstorm initiated a strong suction in the eaves, the overhanging part of the roof. Simultaneously, there is a significant negative wind pressure on the outward sides of the roof. This combination triggered the initiation of roof damage through the eaves. Subsequently, the wind enters the interior of the building, causing an uplift of the roof by increasing the pressure inside. The heightened wind pressure damaged the entire roofing material, and, depending on the force of the wind, it can ultimately lead to the overturning of the roof. Roof failure is one of the common types of failures during windstorms (Mahendran 1995; Sill and Kozlowski 1997). During Hurricane Harvey in 2017, damage to roof components was reported as the most common type of damage in the Port Aransas Region (Aghababaei et al. 2018).

Damages on Thatched Roof

Thatch roof Fig. 6(a) is common in the affected region, providing a cost-effective and locally resourced roofing option for families below the poverty line in Madhesh province. Fig. 6(b) is an adobe structure with a plastic sheet and tile roof. Structurally thatched roof buildings and plastic roof buildings are similar. These roofs are lightweight and do not require a strong truss framework for support. However, they are vulnerable to moderate winds, due to the lack of structural connectivity and weak roof–wall connections, particularly at corners and perimeters, where flow separations and vortex formation result in high suction pressures. Further, thatch wall with

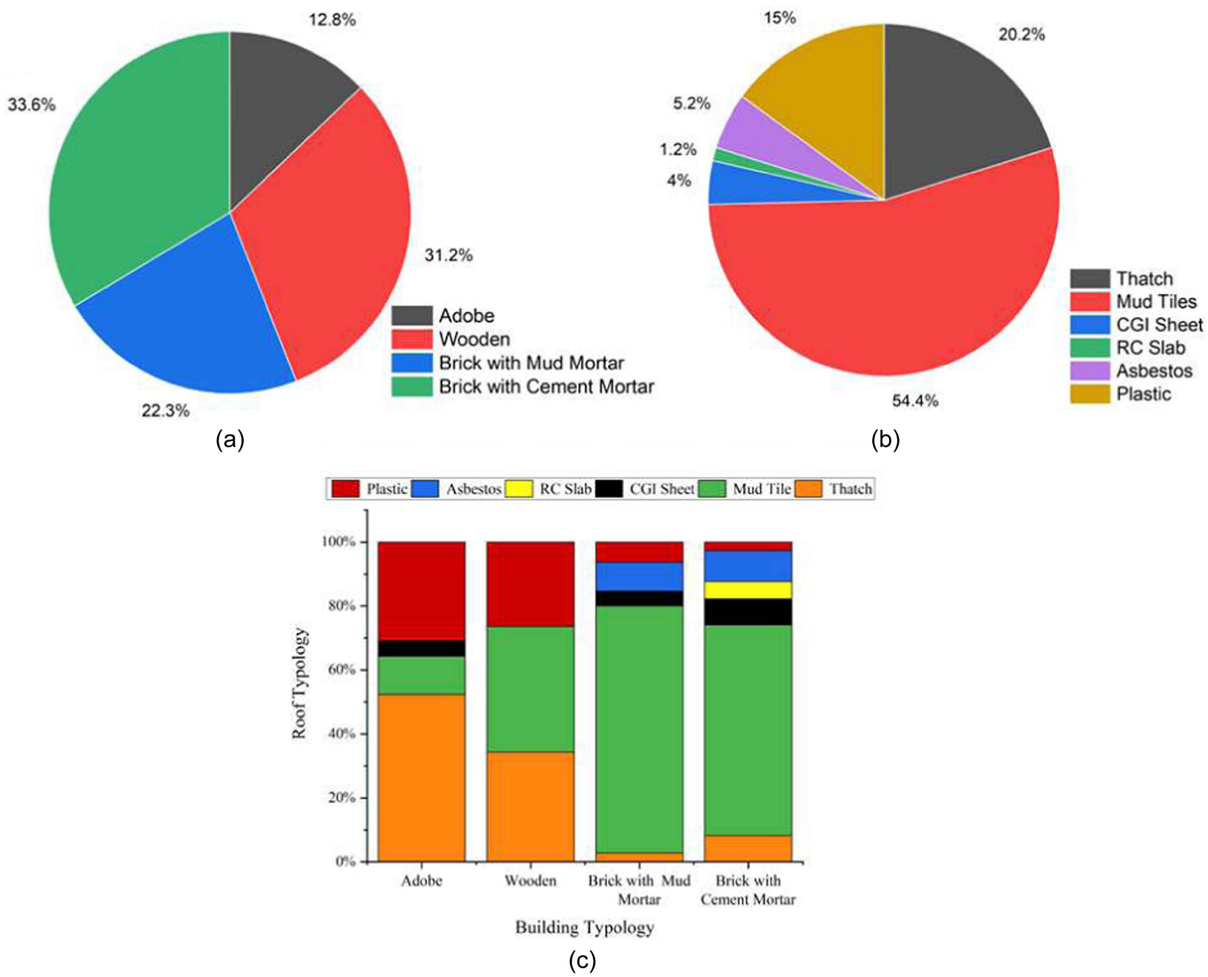

Fig. 4. Results obtained during postwindstorm reconnaissance: (a) building typology; (b) roof typology; and (c) distribution of different roof with different building types.

Table 6. Percentage distribution of only roof failure and roof as well as some parts of building failure of different building typology (first column) and its roof types (first row) considering each building types with specific roof typology is 100%

Building typology	Failure type	Thatch	Mud tiles	CGI sheet	RC slab	Asbestos	Plastic
Adobe	Only roof failure	0.00	20.00	0.0	—	—	0.00
	Building failure	100.00	80.00	100.00	—	—	100.00
Wooden	Only roof failure	11.43	27.50	—	—	—	3.70
	Building failure	88.57	72.50	—	—	—	96.30
Brick with mud mortar	Only roof failure	66.67	29.41	20.00	—	70.0	57.14
	Building failure	33.33	70.59	80.0	—	30.00	42.86
Brick with cement mortar	Only roof failure	66.6	35.42	83.33	0.00	57.1	50.00
	Building failure	33.33	64.58	16.67	100.00	42.86	50.00

mud plaster without connectivity with the ground level or under the foundation has been completely removed.

Damages on Tiled Roof

The damage to tiled roof masonry (Fig. 7) during a storm resulted from a combination of factors, including aging of the roof support structure, intense storm suction pressures, and inadequate tile nailing to the purlin. Poor connection between roofing materials is also why this type of failure occurred. Over time, the support system weakens, making the roof susceptible to external forces. Even a well-tied roof system can be destroyed in an EF5-scale storm. Suction pressures, especially at vulnerable points with decayed tiles, worsen structural vulnerabilities, leading to roof destruction and overall masonry collapse. This highlights the need for regular maintenance and reinforcement of roof support structures to improve resilience against adverse weather conditions.

Damages on CGI Sheet Roof

Houses in Terai, the southern belt of Nepal, typically feature roofs constructed with galvanized iron (CGI) sheets, varying in thickness

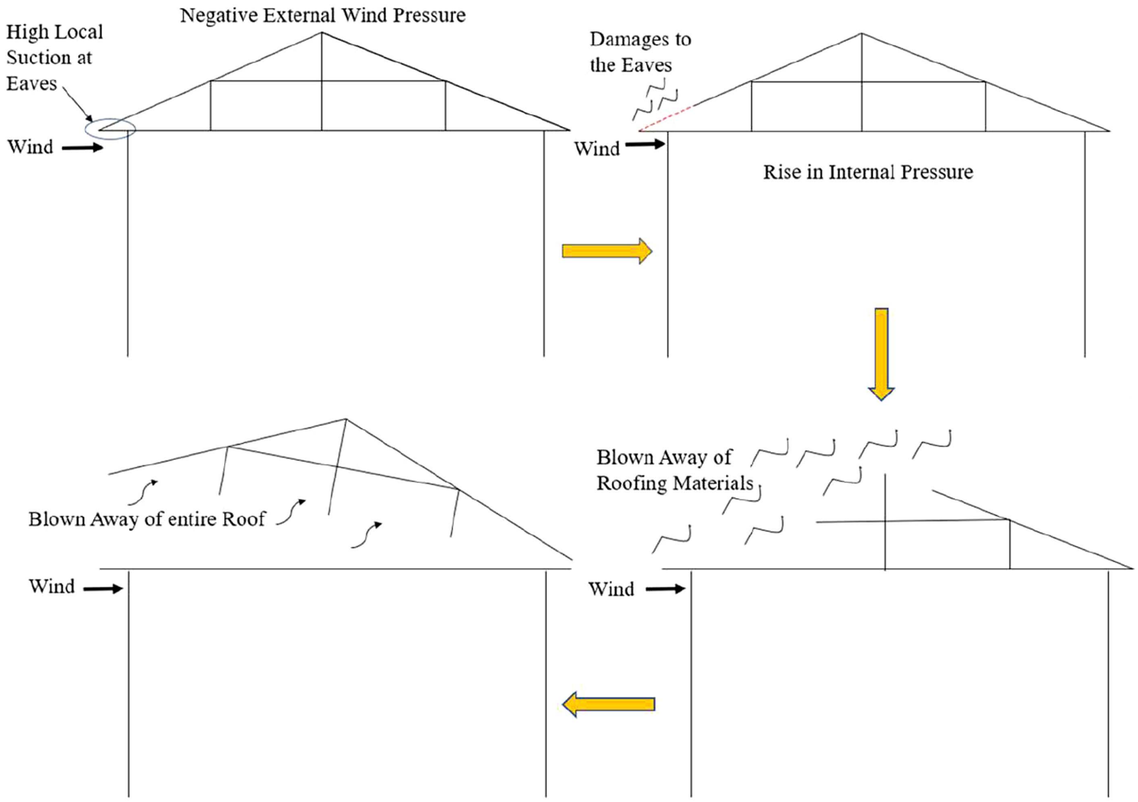

Fig. 5. Roof damage chain during a windstorm. [Reprinted from *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 44 (1–3), Y. Uematsu, M. Yamada, H. Higashiyama, and T. Orimo, "Effects of the corner shape of high-rise buildings on the pedestrian-level wind environment with consideration for mean and fluctuating wind speed," pp. 2289–2300, © 1992, with permission from Elsevier.]

Fig. 6. (a) Thatched roof buildings in relatively less wind affected area of Bara; and (b) collapsed plastic sheet roof and lateral support of bamboo. (Images by Apil KC.)

from 0.22 to 0.64 mm (equivalent to 22 to 32 gauges), fastened to purlins using screws or nails. Many houses with CGI roofing, depicted in, suffered partial or complete damage. The widespread use of CGI sheets in rural areas is attributed to their affordability and durability; however, insufficient consideration for wind effects results in significant damage during windstorms. CGI sheets are frequently lost at roof edges or corners where wind pressure is highest, peeling off in one or more rows from the edges or corners toward the roof center. Inadequate fastening and connections, particularly with toe-nailed connections between purlins and rafters, contribute to this issue (Morrison and Kopp 2011). Timber section failures in purlins indicate insufficiency to withstand wind force, leading to purlin breakage and CGI sheet displacement at roof edges or ends.

Damages on RC Roof

Limited damage to RC buildings primarily resulted from substandard construction. RC buildings with brick masonry and isolated structures have fallen. There is a weak connection among structural elements such as slab, walls, and terrace parapet walls. The main issue observed was damage on the parapet wall (Fig. 8), often lacking proper anchorage with the roof when damaged. In most of the RC buildings that lie in wind paths, some parts of buildings are damaged, but structural failure is not common. Another issue observed on RC buildings in wind-affected areas was the out-of-plane collapse of infill walls, particularly brick walls blown away in the out-of-plane direction. Their lack of connection to the main

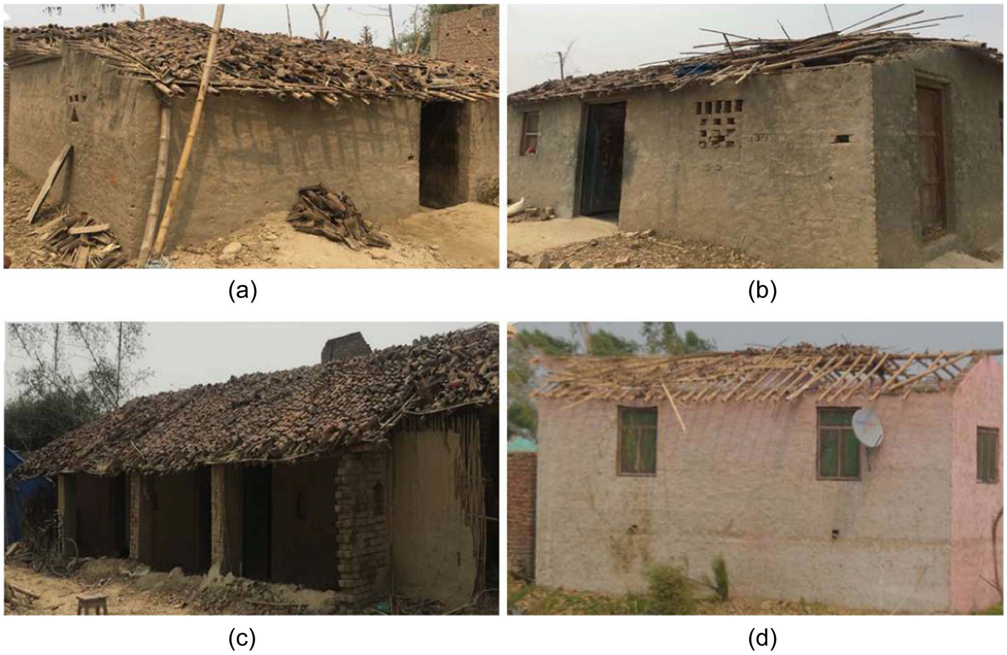

Fig. 7. Damaged tiled roof with no severe damage on the wall. (Images by Apil KC.)

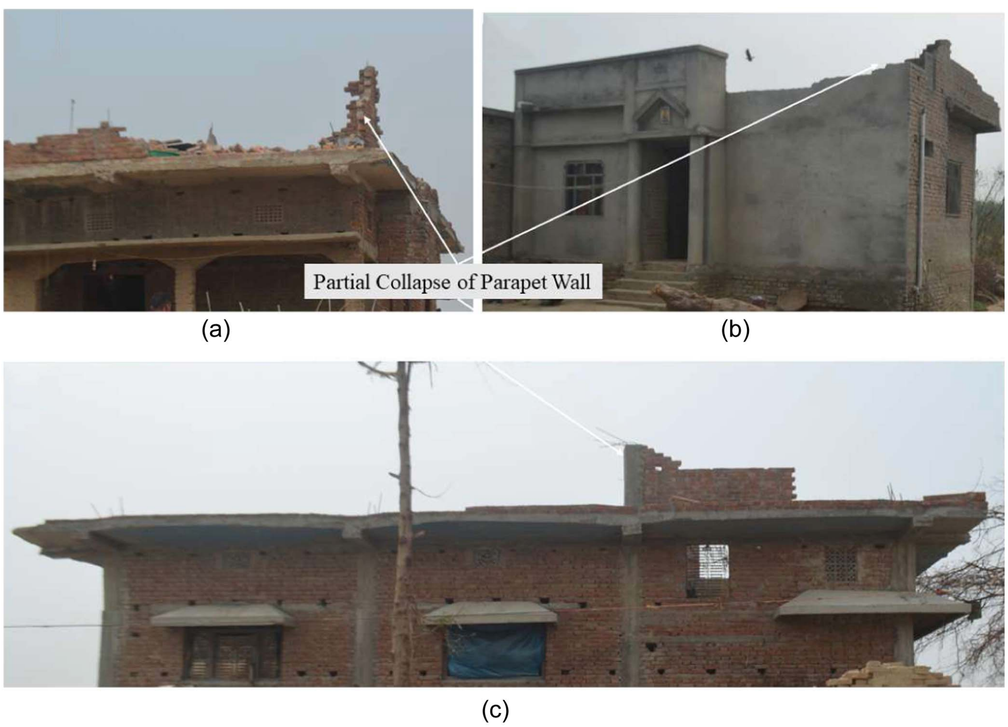

Fig. 8. Partial damages on parapet wall of RC buildings. (Images by Apil KC.)

structural system made them prone to out-of-plane failure under lateral forces.

Failure of Gable Roof End

Gable roofs, characterized by two sloping surfaces, are supported by gable walls or vertical timber struts. Common in masonry buildings, most attics have closed or partially closed spaces using materials such as timber planks, earthen walls, or bamboo mats. During the windstorm, gable roofs with large overhangs were notably damaged, potentially due to increased wind pressure causing CGI sheets to uplift. Traditional roof overhangs in Nepal range from 0.5 to 1.0 m. Displaced heavy roof tiles were frequently observed, and closer inspection revealed inadequate securing of these overhangs to the supporting timber framing below.

Support String Failure

Support strings, mainly galvanized iron (GI) wires, are commonly connected to roof trusses such as tie beams. During windstorms,

J. Perform. Constr. Facil., 2025, 39(1): 04024052

Fig. 9. Round-shaped purlin with poor connection vulnerable to wind. (Images by Apil KC.)

common failures included slipping off from tie beams and breakage. However, these support strings lack proper design to resist windstorms and are not adequately tightened on tie beams or trusses. Round-shaped members make them more vulnerable to wind forces as their connection is not sufficient. There are no design standards or rules for providing support strings to traditional Nepalese roofs. Most commonly observed ones are irregular circular timber purlins, and rafters at the roof ridge have insufficient connections, typically simple lap joints with a single toenail, which, coupled with the irregularity of circular timber, weakens the structure, especially during strong winds (Fig. 9).

Roof-to-Wall Connection Failure

The most common failure in wind-affected areas is the complete blowing away of roofs (Fig. 10). In some buildings, the roof is

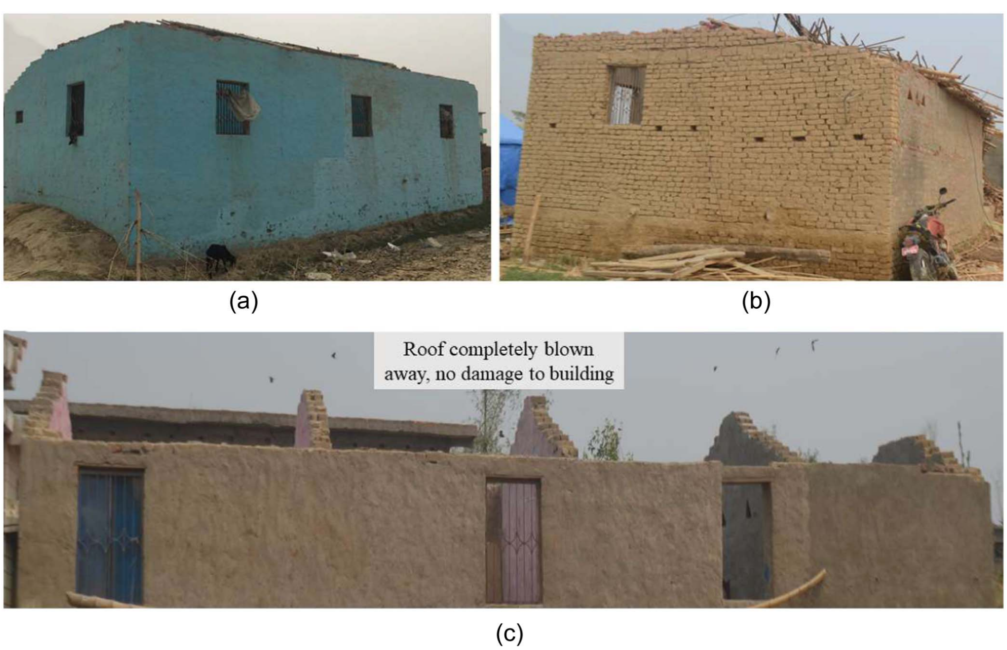

Fig. 10. Complete blown away of roof without much damage on wall. (Images by Apil KC.)

entirely displaced, with minimal damage to the walls and other structural elements. This is primarily attributed to poor connections between the wall and the roof. In many instances, the roof is directly supported by a brick wall at one end and tied to the roof ridge at the other. No straps or plates are employed to link the rafters to the rooftree beams for wind pressure resistance. The connections at the roof ridges are insufficient to endure the force of a windstorm. Typical houses of urban settlements have roof connections at three points: one at the front side supported by vertical struts and two on load-bearing walls, all supported. Despite relying solely on self-weight to resist uplift wind pressure, the lack of rigid connections between walls and roof members renders them vulnerable.

Connection Failure of Wall

Many buildings exhibit weak connections and lack corner posts or stones, isolating two orthogonal walls and leading to out-of-plane failure. This type of failure was notably prevalent in some damaged masonry houses. Such failures are also common in rural area building damages during earthquakes (Sharma et al. 2016; Subedi et al. 2024).

Out-of-Plane Failure

In structures featuring long-span facades and weakened return wall connections, the lack of sufficient bonding in adjacent walls renders them susceptible to lateral loads. The reduced width of walls perpendicular to the storm direction restricts their resistance to lateral force, decreasing the moment of resistance. Buildings with flexible floors are prone to partial or complete overturning, resulting in moderate to severe damage and potential collapse. Notably, in Bara and Parsa, out-of-plane failures frequently originate from inadequate return wall connections, leading to separation and eventual failure of entire walls, as depicted in Fig. 11(a). In certain buildings in wind-affected areas, the aged mud mortar has lost its bonding properties, easily crumbling between fingers, as shown in Fig. 11(b). Additionally, some reinforced brick columns feature only a single reinforcement, illustrated in Fig. 11(c). In RC slab buildings, out-of-plane wall failure has caused significant damage to the RC slab, as depicted in Fig. 11(d).

Complete Structural Collapse

In the central-south windstorm of 2019, numerous buildings experienced substantial damage, with some structures collapsing entirely. Fig 12(a) illustrates a mud mortar brick masonry example of brittle failure, where the structure completely collapsed. In Fig. 12(b), half of the wall collapsed entirely, while the other half remained standing, indicating a potential out-of-plane failure. Fig. 12(c) showcases another instance of brittle brick masonry failure, and, in Fig. 12(d), a building collapsed, leaving only the partition wall standing. The complete collapse of masonry residential buildings was also prominent in a strong windstorm on June 16, 2018, in northern Nigeria (Kafi et al. 2021). Construction and maintenance shortcomings have been recognized as the predominant root causes of most frequently occurring infrastructure collapse during windstorm (Wardhana and Hadipriono 2003).

Damages on Tree and Utility

Numerous utility poles supporting electricity lines collapsed [Fig. 13(a)], potentially due to inadequate lateral support and strong wind currents. Additionally, a bamboo thicket within the area affected by the wind sustained damage [Fig. 13(b)]. Several trees lost branches, and some were uprooted as well [Fig. 13(c)]. In addition, the network of lines in many partially damaged houses has experienced short circuits, and the supply chain for drinking water is also disrupted.

Discussion and Recommendations

In rural Nepal, homes are prone to wind damage due to weak connections, overhangs, insufficient timber support, nonengineered roof configurations, new roofing materials, and the lack of roof-to-wall

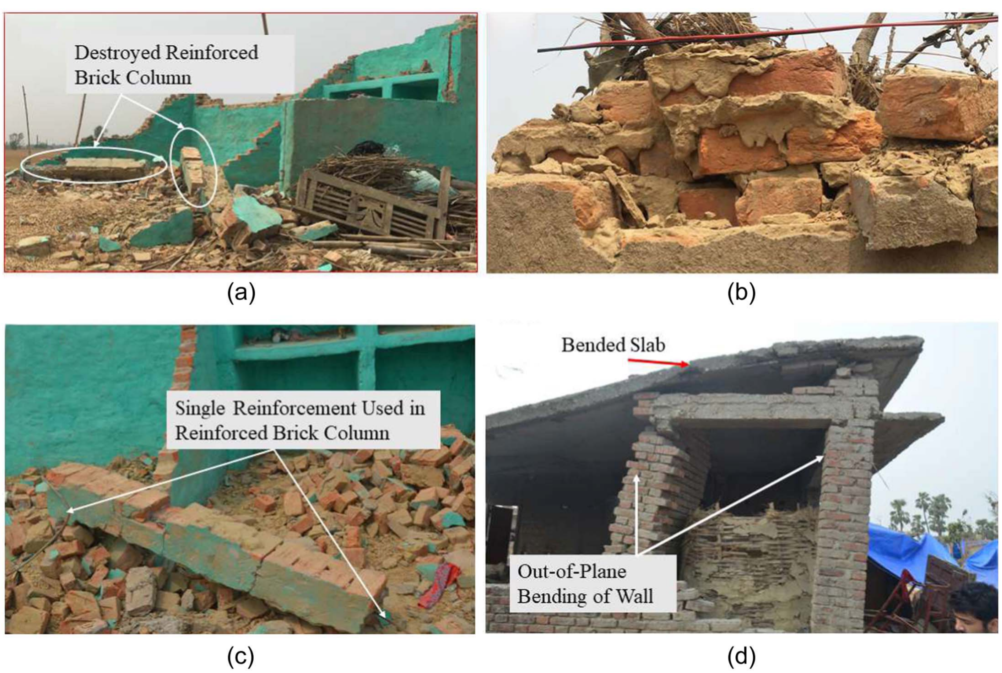

Fig. 11. (a) Out-of-plane failure of wall and destroyed reinforced brick column; (b) thick layer of aged mud mortar used in brick masonry; (c) single reinforced brick column; and (d) out-of-plane bending of wall and bended slab. (Images by Apil KC.)

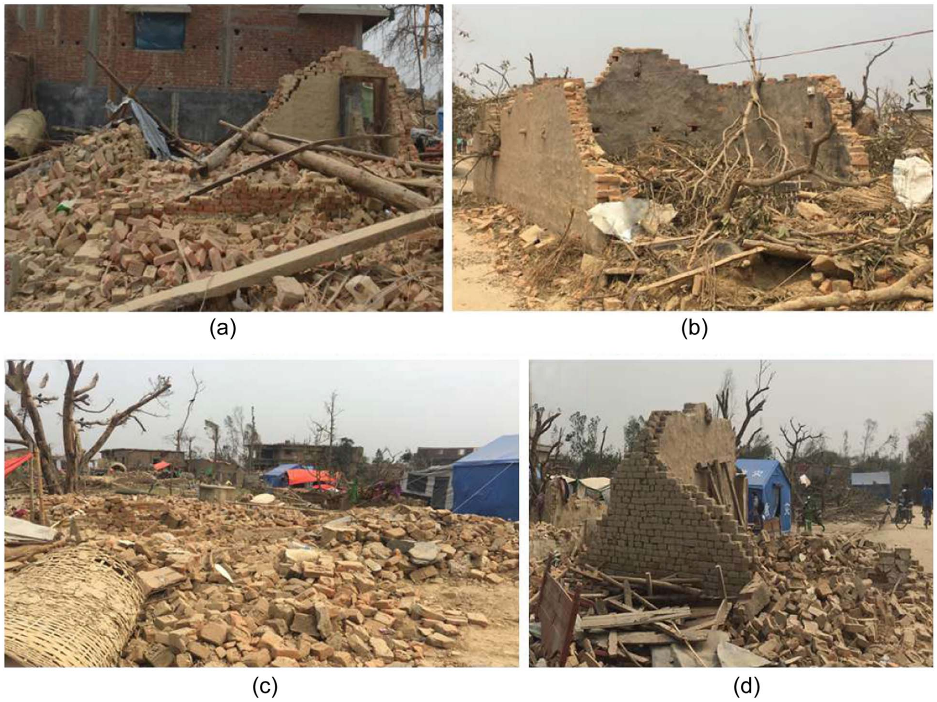

Fig. 12. (a) Brittle failure of brick masonry; (b) half failure of brick masonry; (c) mud mortar brick masonry failure; and (d) collapse of brick masonry with partial partition wall. (Images by Apil KC.)

Fig. 13. (a) Fallen electric pole during wind; (b) damaged bamboo thicket; and (c) some debarked tree. (Images by Apil KC.)

connections. During windstorms, structures often fail at gable roof ends, edges, ridges, and pull-through points and experience roof overturning, resulting in complete detachment. From building code perspective, Nepal currently does not have any comprehensive code for windstorms, especially in rural or semiurban buildings, as this is the first recorded event of its kind in recent history. While Nepal has recently revised its seismic code following the 2015 Gorkha earthquake, poor implementation remains a significant problem. Given that climate change has increased the occurrence of unpredictable windstorms in many areas, including Nepal, this presents a perfect opportunity to study the phenomenon and develop appropriate codes.

Based on reconnaissance, the following preliminary recommendations are made, which could be generalized in building resilient structures in other contexts as well.

- National building codes should be implemented to ensure load-bearing masonry walls are adequately anchored and reinforced to resist lateral forces and non-load-bearing masonry walls are adequately anchored to the supporting structure. Further, the local governments could work closely with locals to enhance the structural resilience of many nonengineered buildings, with locally available resources and easier construction technology.
- Codes for CGI sheet roofs, asphalt sheet roofs, and the sizing and connection of wooden members should be developed, as these are commonly used in rural areas, but standardized codes are currently lacking. Standard construction techniques of anchoring roofing element with the wall could also be the initial stage for this.
- Building frames and masonry walls must be designed not only to resist vertically acting dead and live loads but also to have sufficient lateral strength to withstand wind forces. Support columns or posts must be safely anchored to the roof and foundation.
- The quality of residential construction to mitigate wind-induced damage should be enhanced, potentially through developing a 'deemed to comply' standard in Nepal, further improving wind resilience.
- Resources should be allocated to develop a sophisticated severe weather forecasting system tailored to Nepal's unique weather patterns. Real-time data collection for accuracy should be integrated, advanced numeric weather models should be invested in, and extensive training to meteorological personnel should be provided for precise forecasts and timely warnings, including tornadoes. Preventive measures such as tying roof cladding with ropes, wires, or metal straps and anchoring posts with transverse anchor members to prevent the blowing off thatched roofs should be implemented, thereby minimizing structural damage during windstorms.
- Hipped roofs should be encouraged over gabled roofs in windstorm-prone regions based on evidence suggesting higher resistance to local suction pressures, reducing the risk of roof damage.
- The resistance of roofing systems should be improved by providing concrete restraining strips over tile cladding roofs at suitable intervals, anchored to main rafters, to resist uplift forces better and prevent damage to roofing materials during windstorms.
- Galvanized 'U' hook bolts instead of 'J' bolts should be recommended for attaching AC claddings to rafters/purlins in low-rise industrial structures, ensuring stronger connections that can withstand fluctuating wind forces.
- The lateral resistance of walls in low-rise industrial buildings should be enhanced by installing continuous RC bond beams at the top and utilizing RC columns to support roof trusses instead of brick pilasters, thereby preventing progressive collapse during windstorms.
- Suitable roof bracing should be provided and anchorage, bracing, and continuity in building design ensured to optimize structural integrity and increase resistance to wind forces, thus minimizing the risk of structural failure and enhancing overall safety.

Conclusions

The hurricane affected around 10 villages along its path, with households ranging from 100 to 500 each, with more than 80% of lower-income households reporting damage. The scattered settlement pattern in the Terai area and weak building structures facilitated the storm's destructive impact. Conversely, the storm pattern was disrupted in urban areas with stronger buildings, reducing the wind strength. Weak structural elements contributed significantly to vulnerability, including poor joints, roof–wall linkages, and wall–foundation connections. Based on the reconnaissance survey, the following conclusions are derived. Damage to dwelling units often begins at high wind pressure points such as roof eaves, corners, and wall corners due to inadequate construction standards. Single-story adobe buildings are prone to collapse under lateral and uplift wind forces. In unreinforced masonry, roof failures are common due to poorly tied purlins and roofing materials, as well as weak connections between the roof and walls. Brick masonry failures result from strong winds, thick aged mortar, and insufficient connections between lateral walls. While mud mortar is commonly used, some reinforced brick columns only have single reinforcement. Conversely, well-constructed reinforced concrete buildings, including multistory structures, show resilience against windstorms, highlighting their strength against extreme lateral forces.

Data Availability Statement

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

References

Aghababaei, M., M. Koliou, and S. G. Paal. 2018. "Performance assessment of building infrastructure impacted by the 2017 Hurricane Harvey in the Port Aransas region." *J. Perform. Constr. Facil.* 32 (5): 04018069. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001215.

Alam, M. R., A. B. M. A. Kaish, M. F. M. Zain, S. K. Dev, and M. S. Mahzabin. 2017. "Vulnerability assessment and construction recommendations of local houses in the cyclone prone coastal areas of Bangladesh." *Int. J. Disaster Risk Reduct.* 21 (Mar): 118–130. https://doi.org/10.1016/j.ijdrr.2016.10.010.

Census. 2021. "National population and housing census 2021: Results." Kathmandu, Nepal: Government of Nepal.

Chapagain, D. 2024. "Detection and attribution of spatiotemporal trends of climatic disaster mortality in Nepal." Doctoral dissertation, Dept. of Agriculture, Universitäts-und Landesbibliothek Bonn.

Chettri, N., G. Dhaurali, T. Neopaney, T. Cheki, and D. Gautam. 2022. "Wind vulnerability and strengthening of Bhutanese vernacular roofs." *Geomatics Nat. Hazards Risk* 13 (1): 1511–1534. https://doi.org/10.1080/19475705.2022.2086830.

DRR (Disaster Risk Reduction) Portal. 2020. "Nepal disaster risk reduction portal." Accessed November 15, 2023. http://www.drrportal.gov.np/.

Eamon, C. D., P. Fitzpatrick, and D. D. Truax. 2007. "Observations of structural damage caused by Hurricane Katrina on the Mississippi Gulf Coast." *J. Perform. Constr. Facil.* 21 (2): 117–127. https://doi.org/10.1061/(ASCE)0887-3828(2007)21:2(117).

Gautam, D., R. Adhikari, P. Jha, R. Rupakhety, and M. Yadav. 2020. "Windstorm vulnerability of residential buildings and infrastructures in south-central Nepal." *J. Wind Eng. Ind. Aerodyn.* 198 (Mar): 104113. https://doi.org/10.1016/j.jweia.2020.104113.

Gautam, D., and H. Chaulagain. 2016. "Structural performance and associated lessons to be learned from world earthquakes in Nepal after 25 April 2015 (M_W 7.8) Gorkha earthquake." *Eng. Fail. Anal.* 68 (Oct): 222–243. https://doi.org/10.1016/j.engfailanal.2016.06.002.

Kafi, K. M., A. S. Barau, and A. Aliyu. 2021. "The effects of windstorm in African medium-sized cities: An analysis of the degree of damage using KDE hotspots and EF-scale matrix." *Int. J. Disaster Risk Reduct.* 55 (Mar): 102070. https://doi.org/10.1016/j.ijdrr.2021.102070.

Kafle, S. K. 2017. "Disaster risk management systems in South Asia: Natural hazards, vulnerability, disaster risk and legislative and institutional frameworks.” *J. Geogr. Nat. Disasters* 7 (3): 207. https://doi.org/10.4172/2167-0587.1000207.

Karki, B. K., K. Lamichhane, L. Joshi, K. C. Raj, M. K. Sah, M. Pathak, and K. R. Karki. 2024. “Risk assessment of heavy metals in the major surface water system of Nepal with potential remediation technologies.” *Environ. Challenges* 14 (Jan): 100865. https://doi.org/10.1016/j.envc.2024.100865.

KC, R., K. Sharma, B. K. Dahal, M. Aryal, and M. Subedi. 2024. “Study of the spatial distribution and the temporal trend of landslide disasters that occurred in the Nepal Himalayas from 2011 to 2020.” *Environ. Earth Sci.* 83 (1): 42. https://doi.org/10.1007/s12665-023-11347-7.

Khajwal, A. B., and A. Noshadravan. 2024. “Enhancing post-hurricane regional loss assessment with crowdsourcing: A probabilistic inference approach.” *Int. J. Disaster Risk Reduct.* 107 (Jun): 104456. https://doi.org/10.1016/j.ijdrr.2024.104456.

Lotay, Y. 2015. *Wind induced damage to roofs and mitigations: A comparative study on roofs in Bhutan and Japan*. Kobe, Japan: Asian Disaster Reduction Center.

Lozano, J.-M., and I. Tien. 2023. “Data collection tools for post-disaster damage assessment of building and lifeline infrastructure systems.” *Int. J. Disaster Risk Reduct.* 94 (Aug): 103819. https://doi.org/10.1016/j.ijdrr.2023.103819.

Mahendran, M. 1995. “Wind-resistant low-rise buildings in the tropics.” *J. Perform. Constr. Facil.* 9 (4): 330–346. https://doi.org/10.1061/(ASCE)0887-3828(1995)9:4(330).

Mäkelä, A., R. Shrestha, and R. Karki. 2014. “Thunderstorm characteristics in Nepal during the pre-monsoon season 2012.” *Atmos. Res.* 137 (Feb): 91–99. https://doi.org/10.1016/j.atmosres.2013.09.012.

Masoomi, H., M. R. Ameri, and J. W. van de Lindt. 2018. “Wind performance enhancement strategies for residential wood-frame buildings.” *J. Perform. Constr. Facil.* 32 (3): 04018024. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001172.

McDonald, J. R., K. C. Mehta, D. A. Smith, and J. A. Womble. 2010. “The enhanced Fujita scale: Development and implementation.” In *Proc., Forensic Engineering 2009: Pathology of the Built Environment*, 719–728. Reston, VA: ASCE.

Meena, S. R., O. Ghorbanzadeh, and T. Blaschke. 2019. “A comparative study of statistics-based landslide susceptibility models: A case study of the region affected by the Gorkha earthquake in Nepal.” *ISPRS Int. J. Geo-Inf.* 8 (2): 94. https://doi.org/10.3390/ijgi8020094.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen. 2012. “The impact of climate change on global tropical cyclone damage.” *Nat. Clim. Change* 2 (3): 205–209. https://doi.org/10.1038/nclimate1357.

Messmer, M., and I. Simmonds. 2021. “Global analysis of cyclone-induced compound precipitation and wind extreme events.” *Weather Clim. Extremes* 32 (Jun): 100324. https://doi.org/10.1016/j.wace.2021.100324.

Morrison, M. J., and G. A. Kopp. 2011. “Performance of toe-nail connections under realistic wind loading.” *Eng. Struct.* 33 (1): 69–76. https://doi.org/10.1016/j.engstruct.2010.09.019.

Mukhopadhyay, P., and S. C. Dutta. 2018. “Indian cyclones and earthquakes: Their impact on structures.” In *Exploring natural hazards*, 87–110. Boca Raton, FL: CRC Press.

Nadim, F., O. Kjekstad, P. Peduzzi, C. Herold, and C. Jaedicke. 2006. “Global landslide and avalanche hotspots.” *Landslides* 3 (2): 159–173. https://doi.org/10.1007/s10346-006-0036-1.

Oey, L. Y., T. Ezer, D. P. Wang, X. Q. Yin, and S. J. Fan. 2007. “Hurricane-induced motions and interaction with ocean currents.” *Cont. Shelf Res.* 27 (9): 1249–1263. https://doi.org/10.1016/j.csr.2007.01.008.

Pokharel, A. K. 2022. “Straight-line winds hit parts of Bara and Parsa districts of Nepal.” *Weather* 77 (5): 164–169. https://doi.org/10.1002/wea.4050.

Rimal, P. 2019. “Bara, Parsa was probably hit by the first wind storm of the country: DHM.” *My Republica*. Accessed November 25, 2023. https://myrepublica.nagariknetwork.com/news/bara-parsa-was-probably-hit-by-the-first-wind-storm-of-the-country-dhm/.

Shanmugasundaram, J., S. Arunachalam, S. Gomathinayagam, N. Lakshmanan, and P. Harikrishna. 2000. “Cyclone damage to buildings and structures—A case study.” *J. Wind Eng. Ind. Aerodyn.* 84 (3): 369–380. https://doi.org/10.1016/S0167-6105(99)00114-2.

Sharma, K., L. Deng, and C. C. Noguez. 2016. “Field investigation on the performance of building structures during the April 25, 2015, Gorkha earthquake in Nepal.” *Eng. Struct.* 121 (Aug): 61–74. https://doi.org/10.1016/j.engstruct.2016.04.043.

Sharma, K., A. KC, M. Subedi, and B. Pokharel. 2018. “Challenges for reconstruction after Mw 7.8 Gorkha earthquake: A study on a devastated area of Nepal.” *Geomatics Nat. Hazards Risk* 9 (1): 760–790. https://doi.org/10.1080/19475705.2018.1480535.

Shay, L. K., P. G. Black, A. J. Mariano, J. D. Hawkins, and R. L. Elsberry. 1992. “Upper ocean response to Hurricane Gilbert.” *J. Geophys. Res.* 97 (C12): 20227–20248. https://doi.org/10.1029/92JC01586.

Shultz, J. M., J. Russell, and Z. Espinel. 2005. “Epidemiology of tropical cyclones: The dynamics of disaster, disease, and development.” *Epidemiol. Rev.* 27 (1): 21–35. https://doi.org/10.1093/epirev/mxi011.

Sill, B. L., and R. T. Kozlowski. 1997. “Analysis of storm-damage factors for low-rise structures.” *J. Perform. Constr. Facil.* 11 (4): 168–177. https://doi.org/10.1061/(ASCE)0887-3828(1997)11:4(168).

Subedi, M., R. KC, K. Sharma, J. Misra, and A. KC. 2024. “Reconnaissance of the effects of the M_W5.7 (M_L6.4) Jajarkot Nepal earthquake of 3 November 2023, post-earthquake responses, and associated lessons to be learned.” *Geosciences* 14 (1): 20. https://doi.org/10.3390/geosciences14010020.

Taillie, P. J., R. Roman-Cuesta, D. Lagomasino, M. Cifuentes-Jara, T. Fatoyinbo, L. E. Ott, and B. Poulter. 2020. “Widespread mangrove damage resulting from the 2017 Atlantic mega hurricane season.” *Environ. Res. Lett.* 15 (6): 064010. https://doi.org/10.1088/1748-9326/ab82cf.

Wardhana, K., and F. C. Hadipriono. 2003. “Study of recent building failures in the United States.” *J. Perform. Constr. Facil.* 17 (3): 151–158. https://doi.org/10.1061/(ASCE)0887-3828(2003)17:3(151).