Seismic Fragility Curves for Non-Engineered Low-Rise Commercial Building in Far Western Nepal : A Case Study of Darchula

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Abstract

Seismic vulnerability assessment of non-engineered reinforced concrete (RC) buildings in Far Western Nepal, including Darchula, is crucial due to their inadequate structural performance under earthquake loading. These buildings, typically designed for gravity loads, often feature soft-story mechanisms caused by weak ground stories, making them highly susceptible to seismic failure. This study evaluates the seismic performance of three low-rise (5-story) RC structures using capacity curves, fragility curves, and failure mapping techniques. The capacity curve analysis reveals that NERcA exhibits the weakest base shear capacity, while NERcC shows the highest strength, indicating variations in construction quality and reinforcement detailing. Failure mapping demonstrates

that plastic hinges form primarily in columns rather than beams, contradicting the column-weak-beam design philosophy, and soft-story failure is evident due to irregular stiffness distribution. Fragility analysis further highlights the high probability of failure at lower spectral displacements, with steep fragility curves indicating significant vulnerability, even under moderate seismic loads. The results underscore the need for seismic retrofitting, improved construction practices, and adherence to modern seismic codes to enhance structural resilience. Implementing these measures is critical to reducing seismic risks and preventing catastrophic failures in earthquake-prone regions.

Keywords: *Non-engineered buildings, HAZUS methodology, Fragility Curve, Pushover analysis*

Introduction

Nepal, located in the seismically active region, experiences frequent earthquakes due to the convergence of the Indian and Eurasian tectonic plates shown in Figure 1. While the majority of earthquakes in Nepal have magnitudes between 4 and 6 and typically cause little to no damage, those exceeding magnitude 6.5 have historically resulted in significant destruction. Major earthquakes, such as those in 1833, 1934, 1980, 1988, 2011, and 2015, have highlighted the vulnerability of the country, with damage influenced by factors like energy release, duration of shaking, focal depth, and the resilience of building infrastructure in Nepal (Chaulagain et al., 2018). Reinforced concrete (RC) buildings are very common in Nepal.

Nowadays the construction of RC buildings is growing rapidly. In Nepal, many building codes are developed based on the type of buildings and materials to be constructed. Codel provision was also revised based on the seismic venerability in the structures. To construct earthquake-resisting buildings, it is important to follow the codel provision but for many reasons, people construct RC buildings without consulting with an engineer and they usually do not follow the codel provisions (Paudel et al., 2024; Sapkota et al., 2024). Non-engineered low-rise commercial buildings are widespread in developing regions like Khalnga Darchula, particularly in earthquake-prone areas such as Far Western Nepal (Bohara, 2023). These buildings are typically constructed with little or no professional engineering oversight, relying instead on local masons and traditional construction practices. Due to limited access to resources, many buildings are constructed by local masons without proper engineering guidance, similar to construction practices in Northeastern India (Chandra Dutta et al., 2021). The vulnerability of these structures is exacerbated by poor design and construction quality, making them prone to collapse during seismic events. The absence of proper design standards, poor construction quality, irregular mass distribution, and irregular infill wall distributions often lead to increased susceptibility to earthquake-induced damage (R. K. Adhikari & D’Ayala, 2020; Gautam et al., 2015; Parajuli & Kiyono, 2015; Poudel & Chaulagain, 2024).

Recent studies in regions with similar building typologies, including parts of Northeastern India and Nepal, highlight that many non-engineered structures, especially those featuring reinforced concrete (RC) frames with infilled masonry, are highly vulnerable in seismic zones (Chandra Dutta et al., 2021). The lack of uniformity in infill walls and inadequate design and construction quality further exacerbates this vulnerability (KARAŞİN et al., 2017; Varum et al., 2018). Additionally, the practice of using open ground storeys, irregularity in mass distribution without sufficient engineering input is common, often leading to severe structural weaknesses during earthquakes (Abdel Raheem et al., 2018; Khanal & Chaulagain, 2020; Krishnan & Thasleen, 2020; Özmen et al., 1998; Ravikumar et al., 2012). The country has experienced numerous devastating seismic events, including the catastrophic 1934 Bihar-Nepal earthquake (Mw 8.0) and the 2015 Gorkha earthquake (Mw 7.8). These events caused widespread damage to infrastructure and resulted in a significant loss of life, particularly in rural and urban areas where non-engineered buildings dominate. Most residential and commercial structures in Nepal are either masonry or reinforced concrete (RC) buildings with masonry infills (Dutta et al., 2015; Gautam & Chaulagain, 2016).

In the context of low-rise buildings, especially in earthquake-prone regions like Nepal, fragility curves serve a critical role in assessing structural resilience (Chapagain & Chaulagain, 2024). Many low-rise buildings, such as non-engineered residential and commercial structures, are typically built with little or no seismic design consideration. These buildings often use materials like masonry infills, and due to

budget constraints and lack of engineering expertise,
their construction may not meet earthquake-resistant standards. Fragility curves help in evaluating how such buildings are likely to perform under seismic stress, identifying which structural elements are more vulnerable and estimating the probability of different levels of damage (Gautam et al., 2021).

This study focuses on the development of seismic fragility curves for non-engineered low-rise commercial buildings in Darchula, Far Western Nepal. Fragility curves are an essential tool for assessing the probability of structural damage under varying earthquake intensities. By employing a nonlinear static analysis approach, this research aims to quantify the vulnerability of these buildings, considering local construction practices and design deficiencies. The insights gained from this study can inform future construction guidelines, helping to mitigate the risks associated with non-engineered buildings in high seismic regions.

Moreover, the results of this research may be applicable not only in Darchula but in other regions with similar building practices, thereby contributing to the broader understanding of seismic risk in rural and underserved areas. The findings can serve as a critical resource for policymakers, engineers, and builders in enhancing the resilience of low-rise commercial structures against earthquake hazards.

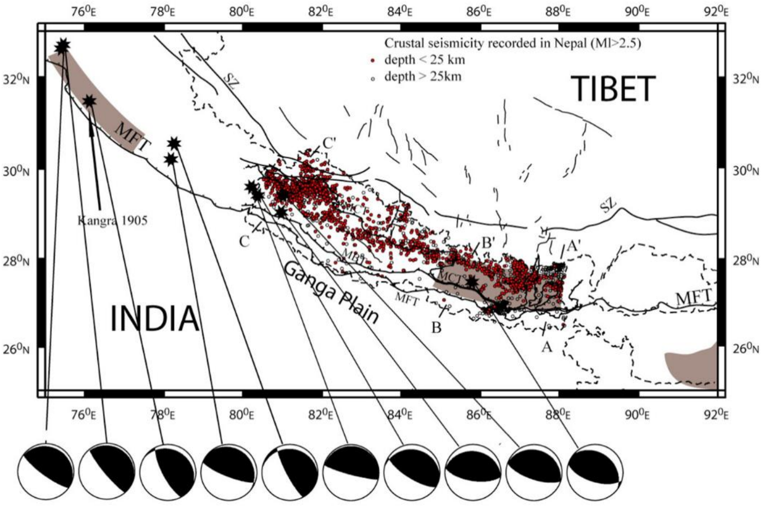


Fig. 1. Historical earthquakes in the Himalayan oF Nepal (monitored between 1985–1998) (Jouanne et al., 2004)

Brief description of Code based building construction

The Nepal National Building Code (NBC), developed by the Department of Urban Development and Building Construction, was first drafted in 1993–1994 and adopted in 2003 after 1988 earthquake in Nepal (Fujiwara et al., 1989). It became part of the official gazette in 2006. Compliance with the NBC 1994 is mandatory in all municipalities and some rural municipalities in Nepal. However, before the NBC promulgation, various international codes, such as Indian, British, and American standards, were utilized for structure construction in Nepal. Since the enactment of the Building Code Act in 1994 and its enforcement in 2003, urban housing construction in

Nepal has advanced significantly, with many new structures adhering to the Nepal National Building Code (NBC) to meet seismic demands at that time. Many other provisions and rule have been developed including NBC 201, 202, and 205, offer a set of guidelines designed to improve the safety and durability of residential and commercial buildings, particularly for low- to low-rise structures. The mandatory rules of thumb (MRT) provided by NBC have been widely adopted for owner-built houses, offering ready-to-use dimensions and detailing for beams, columns, and other structural components. NBC 205: 2012 (MRT rule) for example, recommends that columns for buildings up to three storeys have a minimum size of 300mm x 300mm with at least four 12-16mm diameter bars and appropriate spacing of stirrups to improve lateral load resistance (Mahal & Kathmandu, 2070). The NBC 205 again revised with some new advanced guidelines in 2024 for low-rise buildings up to 3 stoeyes. The Nepal National Building Code (NBC) 205:2024, titled "Ready-to-Use Detailing Guideline for Low-Rise Buildings," offers standardized design and detailing practices to enhance the structural integrity and seismic resilience of low-rise constructions in Nepal (NBC 205, 2024). The code specifies dimensions and reinforcement details for structural elements based on building height and seismic considerations such as in three-story buildings, recommended beam sizes include 250 mm x 355 mm and 300 mm x 380 mm, with corresponding reinforcement details provided to ensure adequate strength and ductility in structures. Reinforcement bars are specified to meet the minimum yield strength of 500 N/mm^2, conforming to NS: 191-2046 standards. The code emphasizes the use of closed stirrups with 135° hooks and a minimum hook length of 65 mm to enhance confinement in columns and beams. Despite the existence of numerous building codes in Nepal, including the National Building Code (NBC) and additional guidelines like IS 1893, construction practices in rural and hilly regions frequently stray from these standards, resulting in structural shortcomings and increased vulnerability to earthquakes (R. K. Adhikari & D'Ayala, 2020; Dutta et al., 2015; Sehgal apoorva., 2017). This problem is particularly noticeable in areas such as Darchula, where both reinforced concrete (RC) and unreinforced stone masonry buildings are built with insufficient compliance to code requirements (Bohara, 2023). These infractions severely weaken the seismic performance of structures, highlighted by the common occurrence of soft-story designs in the area. Such buildings, often featuring an open ground level for commercial purposes, do not possess adequate lateral stiffness to withstand earthquake forces, which directly violates NBC regulations. Furthermore, issues in reinforcement detailing, like improper beam-column connections, incorrect stirrup spacing, and inadequate rebar anchorage, compromise the structural stability of these buildings. Such practices are widespread in Mahakali Municipality, where the mix of traditional construction methods and a lack of technical oversight intensifies these problems. The region's hilly landscape and dependence on non-engineered methods heighten the risk, making low cost nonengineered Rc buildings vulnerable to failure during seismic activities. Tackling these issues necessitates not only stricter enforcement of building codes but also broad initiatives to raise awareness and build capacity for earthquake-resistant construction practices in rural area.

Building Typologies

The following building types are commonly found in Darchula, highlighting their characteristics and vulnerabilities:

Traditional Construction (unreinforced masonry):

Stone in mud, dry stone and block or brick-in-mud buildings**:** These structures are prevalent in rural areas. Stone-in-mud buildings, using undressed stones, dressed stone and mud mortar, and brick-in-mud buildings, which combine fired bricks with mud mortar, are also susceptible to earthquake damage due to weak tensile strength and poor lateral load performance (See figure 2 (a), (e)).

Modern Masonry:

Brick, Rc block and Stone in cement mortar buildings: This category includes masonry buildings, which utilize fired bricks and block set in cement mortar, offering improved durability compared to traditional methods. Stone masonry buildings with cement mortar also enhance strength but depend on quality construction techniques to withstand seismic conditions as shown in Figure 2.

Reinforced Concrete Buildings:

Non-Engineered RC moment-resisting frame buildings: These buildings feature reinforced concrete frames with unreinforced brick masonry infill walls and these buildings are constructed without considering the codel provision and designed properly. Common in urban and peri-urban areas, these structures often lack proper engineering oversight, resulting in vulnerabilities during earthquakes due to inadequate detailing and design as shown in figure 2.

Engineered RC moment-resisting frame buildings: Representing a more modern approach, these buildings are designed under the supervision of qualified engineers and they include robust connections between beams and columns, providing better performance under seismic forces. The cast-in-situ concrete slabs for floors and roofs further enhance their structural integrity.

Other Building Types:

Mixed buildings: These structures combine elements of traditional and modern construction, such as stone and adobe or brick-in-mud with cement. However, these mixed systems often demonstrate poor performance during earthquakes due to inconsistencies in material strength and load distribution.

Figure 2: Common construction practice in structures in Darchula

Methods and modeling

Studied buildings

To evaluate the seismic performance of typical non-engineered RC buildings in Far Western Nepal, particularly in Darchula, three representative models NERcA (Non-Engineered Reinforced Concrete Model A), NERcB (Non-Engineered Reinforced Concrete Model B), and NERcC (Non-Engineered Reinforced Concrete Model C) were selected. The region is characterized by steep hillsides, poor road connectivity, and limited access to engineering supervision, which has resulted in the widespread construction of low- to mid-rise RC commercial buildings without adherence to seismic codes (Bohara, 2023). These structures are typically built by local masons, using informal techniques and low-strength materials, making them especially vulnerable to earthquake-induced damage. Recent field surveys, including those conducted by the authors, revealed common structural deficiencies such as soft stories, irregular mass distribution, and inadequate reinforcement detailing, which further justify the selection of Darchula as a representative location for seismic fragility assessment (Bohara, 2023). Moreover, there is a lack of existing research focused on seismic risk in this remote region, despite the known exposure and vulnerability. By selecting Darchula, this study aims to fill a critical knowledge gap and provide context-specific insights that can inform risk reduction strategies and retrofitting priorities for similar hilly regions in Nepal and beyond (Bohara et al., 2025).

These models were derived from a detailed field survey of existing RC commercial buildings in the Mahakali Municipality, ensuring their relevance and representativeness of the local building stock. The selection was guided by observed variations in geometry, number of stories, construction quality, and reinforcement detailing. Model NERcA, a compact 4-story commercial building, features a single bay with modest dimensions of 6 m in length and 4 m in breadth, utilizing smaller column sizes of 230 x 300 mm and its 3D view, elevation and plan as shown in Figure 3. In contrast, NERcB also stands at 4 stories but showcases a more extensive footprint of 12 m by 7.5 m and three bays (as shown in Figure 4), allowing for greater interior flexibility. Its larger column dimensions (300 x 300 mm) enhance its structural capacity, making it better equipped to handle both vertical and lateral loads. Model NERcC, the tallest at 5 stories, combines varying story heights (2.8 m for lower stories and 3.2 m for upper stories) and a spacious four-bay layout, ideal for diverse commercial uses (see figure 5). With robust column sizes similar to NERcB, NERcC offers improved structural integrity, crucial for seismic resistance due to its height. Together, these models reflect the evolving architectural landscape in Darchula, highlighting the shift from traditional construction practices to modern, engineered solutions capable of addressing the seismic challenges of the region.

In this study, the structural modeling of the selected
RC buildings (NERcA, NERcB, and NERcC) was carried out using a nonlinear static pushover analysis approach. The models were constructed using lumped plastic hinge elements at both ends of beams and columns to simulate nonlinear behavior, consistent with FEMA-356 (FEMA 356, 2000) recommendations. This method was chosen for its computational efficiency and ability to capture key post-yield performance characteristics of non-engineered RC structures.

The material properties assigned to the models were based on field observations and typical values documented for non-engineered constructions in Far Western Nepal. For concrete, a compressive strength (f'c) of 20 MPa was used, reflecting low-strength concrete commonly mixed on-site. The reinforcement steel was modeled with a yield strength (fy) of 415 MPa, consistent with locally available deformed bars. An elastic modulus of 25 GPa was assumed for concrete and 200 GPa for steel. The models did not explicitly incorporate infill-frame interaction, due to the lack of reliable in-situ data and the variability of infill wall properties and configurations across buildings. However, the absence of this interaction is acknowledged as a limitation in the analysis. The infill walls were assumed to contribute mass but not stiffness, representing a conservative assumption for structures with weak or poorly connected masonry infill. Future studies may incorporate equivalent strut models or panel zone modeling to capture these effects more accurately.

The three selected models exhibit a notable increase in dead loads on the upper stories, primarily due to the additional weight of the walls and the cantilever extensions from the beams. As the height of the buildings increases, the upper floors possess a greater carpet area, attributable to the slabs that extend over the increased beam dimensions. This configuration results in an accumulation of structural loads as one progresses to the upper stories, significantly influencing the overall behavior of the buildings under seismic conditions.

The increased dead load on the upper floors is particularly critical in the context of seismic performance. With the added weight, the demand on the structural elements such as beams and columns increases, necessitating careful consideration of their capacity to withstand lateral forces during seismic events. Furthermore, the cantilevered beams, while providing additional floor space, contribute to increased bending moments and shear forces, which can compromise the integrity of the structure if not adequately designed.

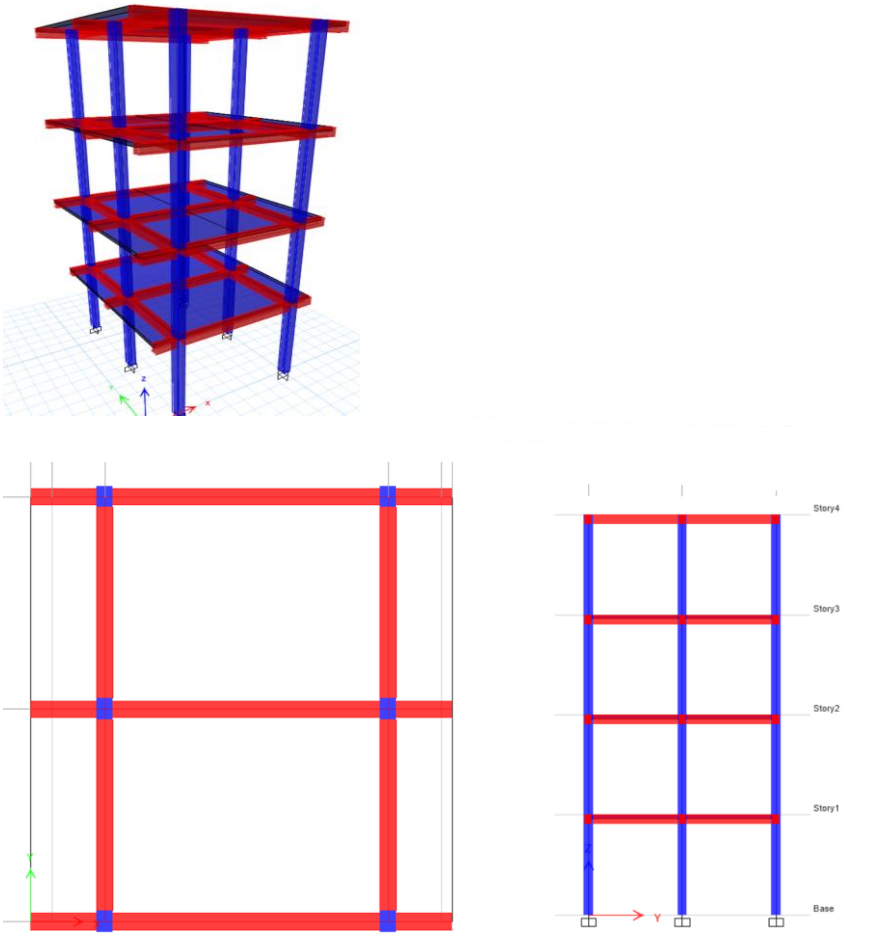


Figure 3. Model NERcA 3D modeling, plan and elevation

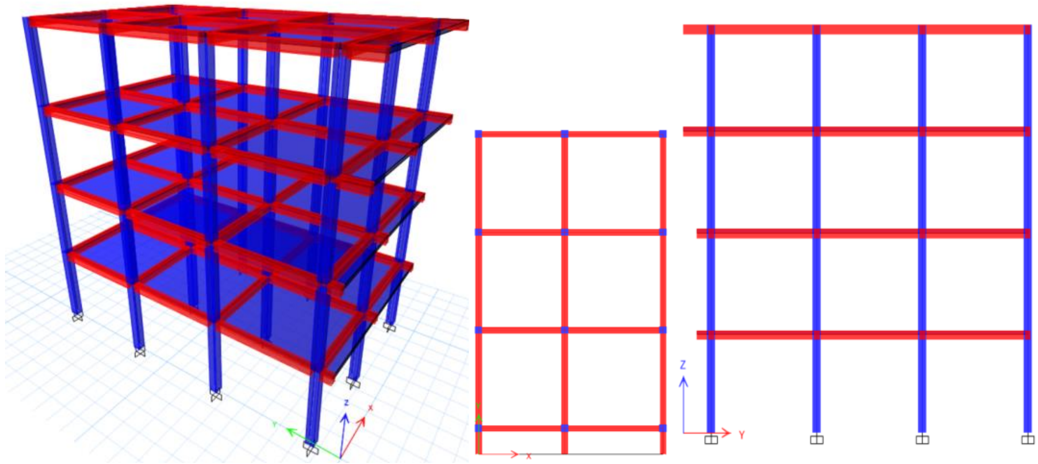


Figure 4. Model NERcB 3D modeling, plan and elevation

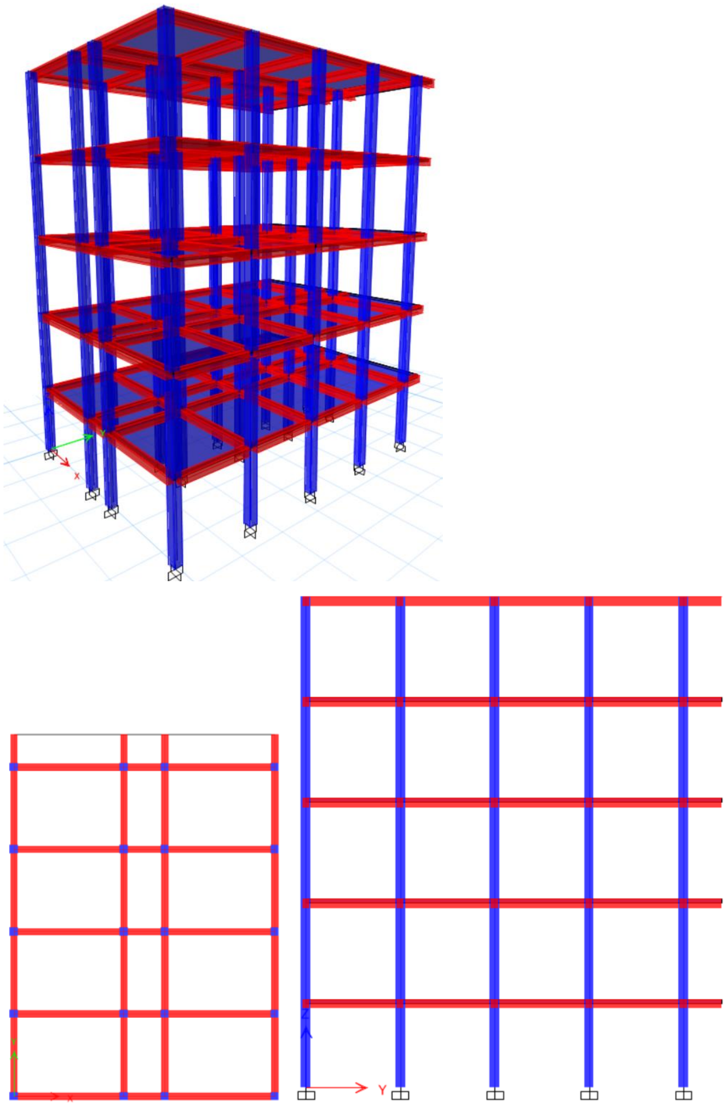


Figure 5. Model NERcC 3D modeling, plan and elevation

Results and discussion

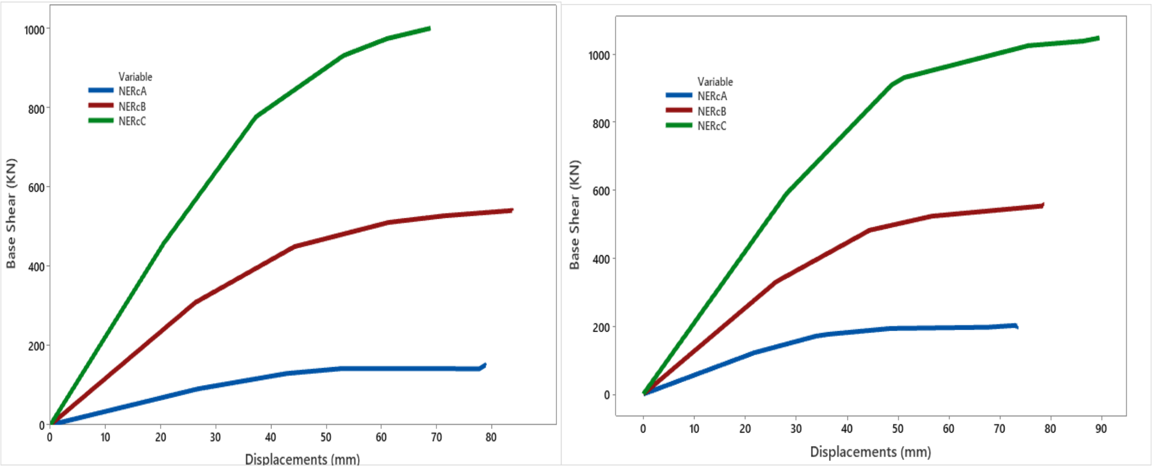
Nonlinear analysis

Nonlinear analysis plays a vital role in assessing the seismic performance of structures, particularly in earthquake-prone areas. In this study, nonlinear static analysis procedures (NSPs), specifically the pushover analysis, were employed due to their relatively simple application. While NDPs offer a more detailed understanding of a structure's response to seismic events, they demand considerable computational resources and time. Recent research has indicated that the results obtained from NDPs such as maximum roof displacements and base shears are often comparable to those derived from NSPs, making NSPs a practical choice for evaluating the seismic behavior of reinforced concrete (RC) frame buildings (Ali & Sanghai, 2021; Bohara & Saha, 2022; Goel RK & Chopra, 2004; Mwafy & Elnashai, 2001). In seismic performance evaluation, a capacity curve is defined by three key control points such as design capacity, yield capacity, and ultimate capacity of the structure. Each of these control points represents a critical phase in the behavior of a structure under increasing lateral loads, offering insight into its strength, deformation, and potential failure mechanisms (Mwafy & Elnashai, 2001).

The nonlinear static pushover analysis in this study was performed using a displacement-controlled approach in both the X and Y directions. A uniform lateral load pattern proportional to the building mass was applied to simulate the distribution of seismic forces across the structure, consistent with recommendations for regular frame systems as outlined in FEMA 356 (FEMA 356, 2000). The models were constructed as three-dimensional RC moment-resisting frames using lumped plastic hinge elements to represent nonlinear behavior. Plastic hinges were defined at both ends of beams and columns based on the ASCE 7-16 (ASCE, 2016), which follow American standards for nonlinear hinge modeling. The default hinge properties including M3 moment hinges for beams and P-M2 (axial-flexure) interaction hinges for columns were assigned to critical locations in the structure. These hinge models account for yielding, post-yield stiffness, and ultimate deformation capacity, ensuring that the simulated behavior reflects realistic inelastic mechanisms observed in non-engineered RC buildings.

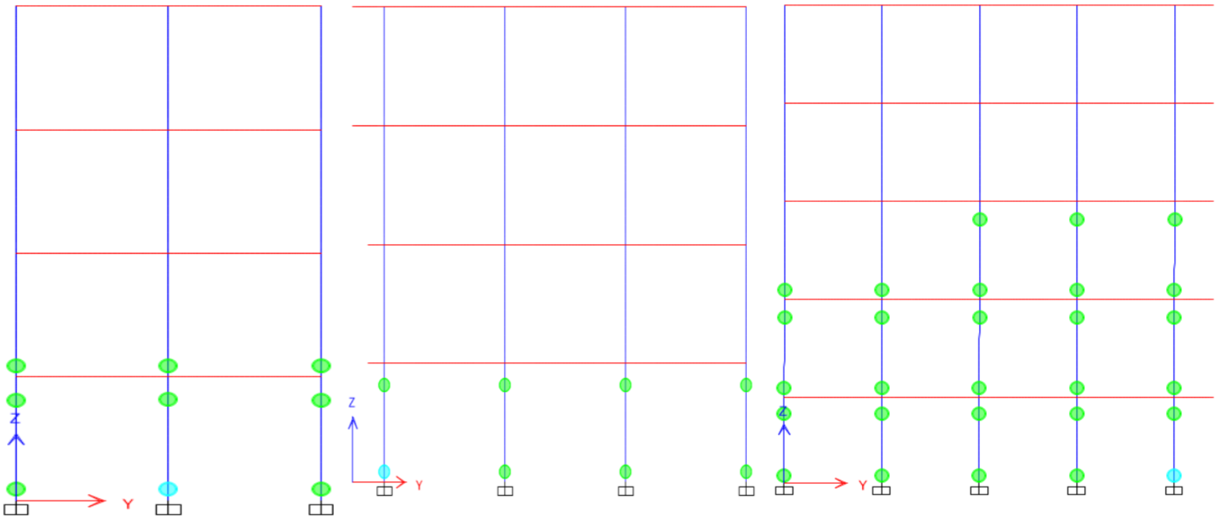
All analyses considered gravity loads comprising full dead load and 25% of the live load, as per common practice in seismic analysis of RC buildings. The control node was located at the roof level to monitor global displacement and identify capacity points (Mazza & Vulcano, 2008). Infill walls were modeled as non-structural mass only, with no stiffness contribution, to reflect construction practices typical in Darchula. These modeling assumptions were made to balance analytical rigor with computational feasibility, and they align with international best practices for fragility assessment using pushover methods.

The seismic performance analysis of three low-rise (4 and 5-storey) non-engineered reinforced concrete (NERc) buildings was conducted to evaluate their structural capacity and failure mechanisms. The capacity curves presented in Figure 6 illustrate the relationship between base shear and top-story displacement in both the x and y directions. Among the models analyzed, NERcA exhibits the lowest base shear capacity, highlighting its weak structural resistance under lateral loads. In contrast, NERcC demonstrates the highest strength, while NERcB falls in between, indicating variations in construction quality and reinforcement detailing. The failure mapping in Figure 7 provides critical insights into hinge formations, revealing that the first plastic hinges predominantly appear in columns rather than beams, contradicting the strong column-weak beam design philosophy recommended in modern seismic codes. The observation of initial plastic hinge formation in columns, rather than beams, highlights deviations from recommended seismic design philosophy. While this study identifies such behavior, detailed analysis of contributing factors such as reinforcement inadequacies and construction deficiencies remains a topic for further investigation. Additionally, the models exhibit soft-story failure, attributed to irregular stiffness distribution across the height of the structures. These findings emphasize the vulnerability of non-engineered buildings to seismic forces and the urgent need for retrofitting measures to enhance resilience and mitigate collapse risks in earthquake-prone regions.



a) b)

Figure 6. Base shear vs Displacement a) Along x axis b) y axis



(a) NERc A (b) NERcB (c) NERcC

Figure 7. Failure mapping

Fragility Curve from Nonlinear Static Pushover Analysis

A fragility curve is a probabilistic tool used in seismic vulnerability assessment to quantify the likelihood of different damage states of a structure under varying levels of seismic intensity (R. Adhikari et al., 2022; AL-saedi & Yaghmaei-Sabegh, 2024). When derived from nonlinear static pushover analysis, fragility curves provide insights into how a building responds to increasing lateral forces, offering a detailed assessment of its vulnerability to earthquakes. The fragility curve is then developed by relating this capacity curve to seismic demand parameters, such as peak ground acceleration (PGA) or spectral displacement (Sd), and determining the probability that the structure will reach or exceed specific damage states. The first step in creating fragility curves is to define different damage states for the building, such as slight, moderate, extensive, and complete damage. These damage states correspond to increasing levels of structural deterioration, from minor cosmetic damage to structural failure. Using the pushover capacity curve, thresholds for each damage state are determined. These thresholds are usually related to key structural responses, such as displacement or deformation levels at critical points (e.g., roof displacement). The fragility curve is expressed as a cumulative probability function, where the x-axis represents the intensity of the earthquake (spectral acceleration) and the y-axis shows the probability that the building will reach or exceed a specific damage state.

In the present study, the fragility curves for reinforced concrete (RC) buildings are developed using the HAZUS (Hazus Earthquake Model Technical Manual Hazus 4.2 SP3, 2020) methodology. HAZUS®-MH MR5, initially developed by the Federal Emergency Management Agency (FEMA) (Fema, 2005) for seismic risk and loss assessment in the U.S., has become widely used around the world due to its adaptability to different building types and seismic environments. The methodology provides a systematic framework for assessing the seismic vulnerability of buildings and infrastructure based on fragility curves. The damage state thresholds are defined in terms of spectral displacement (S_d), based on the yielding (S_{dy}) and ultimate (S_{du}) values derived from the pushover curve and converted into an acceleration-displacement response spectrum (ADRS) format:

Table 1. Damage states for buildings

Damage State	Threshold values of d [mm]
Sd_1	0.7. S_{dy}
Sd_2	$Sd_2 = S_{dy}$
Sd_3	$S_{dy} + 0.25\ (S_{du} - S_{dy})$
Sd_4	S_{du}

Development of Fragility Functions

The fragility curve follows a lognormal distribution and represents the probability of a structure reaching or exceeding a specific damage state under a given seismic intensity (Ahmad et al., 2018; Akbari et al., 2015; Kadid et al., 2008). These curves are constructed using the relationship between seismic demand (such as spectral displacement, S_d) and structural capacity (derived from the capacity curve).

The fragility curve is mathematically expressed as:

$$P[D \geq DS] = \varphi\left[\frac{ln(S_d) - \ln\,(S_{dm})}{\beta}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where:

$P[D \geq DS]$ is the probability of exceeding a particular damage state.

φ is the cumulative distribution function of the standard normal distribution.

S_d is the spectral displacement.

S_{dm} is the median spectral displacement at which the damage stste is expected or occur.

β is the logarithmic standard deviation.

The standard deviation (σ) for each damage state was determined by fitting a normal cumulative distribution function (CDF) to the probabilities listed in Barbat (Barbat et al., 2008) Table 2. For a given structure, the spectral displacement thresholds (Sd1, Sd2, Sd3 and Sd) were established as the mean displacement values corresponding to slight, moderate, extensive, and complete damage states. The optimization process aimed to minimize the sum of squared errors between the empirical probabilities from Table 2 and the CDF values of the normal distribution at these spectral displacement points. By iteratively adjusting σ, the best statistical fit was achieved while keeping the mean values fixed. This procedure was applied independently to each structure and damage state to ensure accuracy in fragility curve development. The fragility curves in the provided figure 8 illustrate the probability of failure of non-engineered Rc (NERcA, NERcB and NERcC) buildings across different damage states slight, moderate, extensive, and complete based on spectral displacement values. The curves indicate that buildings exhibit a significantly higher probability of failure at lower spectral displacements. This suggests that NERc buildings have lower seismic resilience due to inadequate reinforcement detailing, limited ductility, and insufficient lateral strength. The steep slope of the curves, particularly for slight and moderate damage states, further highlights the structural vulnerability of these buildings, emphasizing their susceptibility to seismic demands even at relatively small displacements. These findings reinforce the importance of implementing and enforcing modern seismic design codes to enhance structural safety.

The dispersion (β) for each fragility curve was determined by fitting a lognormal cumulative distribution function to empirical damage probabilities based on Barbat et al. (2008) (Barbat et al., 2008) . An optimization algorithm was used to minimize the sum of squared errors between the fitted CDF and the target data at spectral displacement thresholds corresponding to each damage state. The steepness of the fragility curve for NERcA reflects low dispersion and early structural failure, which is characteristic of buildings with minimal capacity and brittle failure modes. In contrast, the wider dispersion for NERcC indicates a broader range of displacement capacity and uncertainty in performance due to increased complexity and variation in load distribution. It should be noted that variability due to ground motion characteristics and material randomness was not modeled explicitly, and future work may explore these effects using dynamic time-history simulations.

Table 2. developed by Barbat et al to construct fragility curves (Barbat et al., 2008)

Condition	P_β (1)	P_β (2)	P_β (3)	P_β (4)
P_β (1)	0.5	0.119	0.012	0
P_β (2)	0.896	0.5	0.135	0.008
P_β (3)	0.992	0.866	0.5	0.104
P_β (4)	1	0.988	0.881	0.5

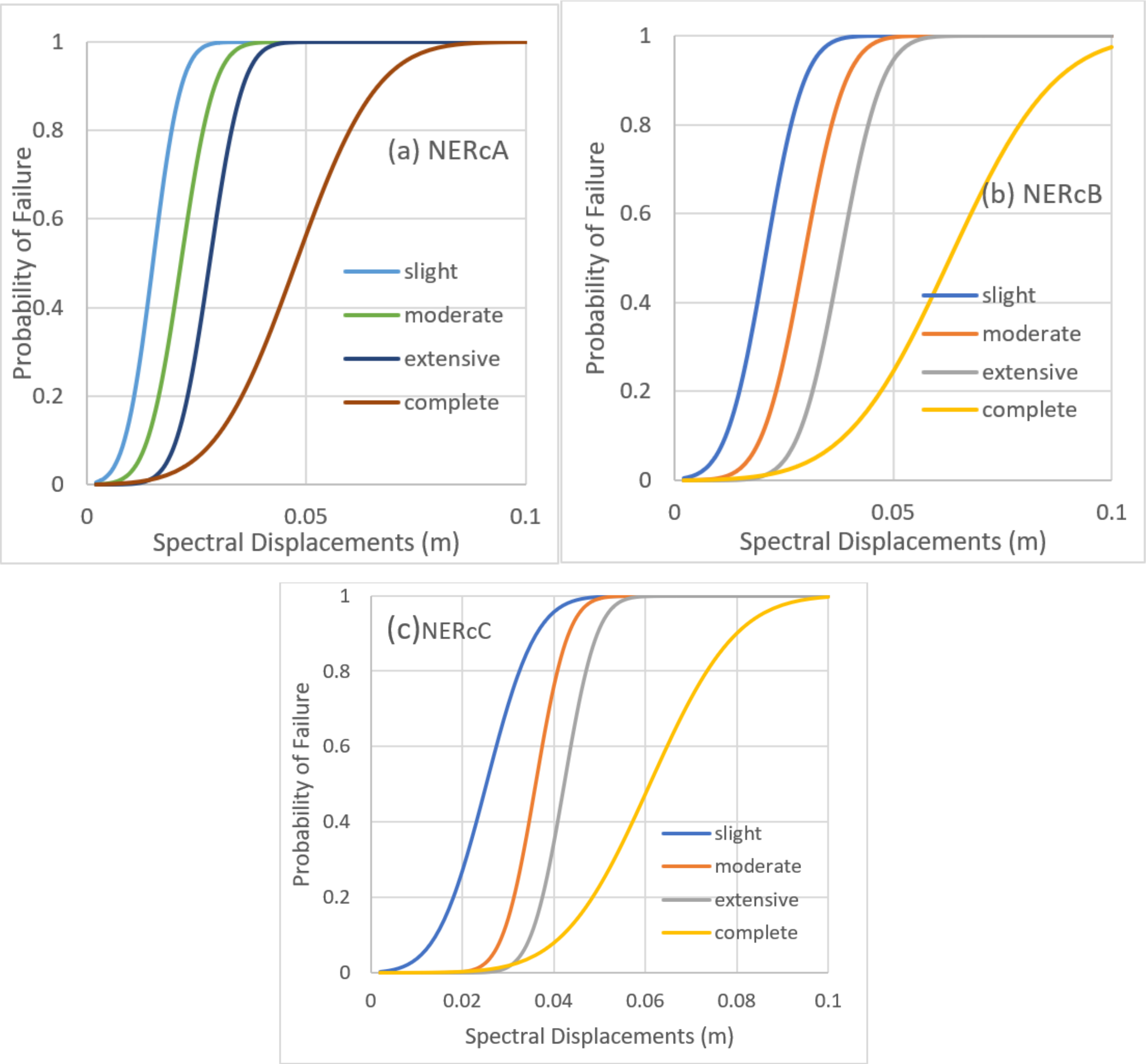


Figure 8 Fragility curves for (a) model A, (b) model B and (c) Model C.

Conclusion

The seismic hazard in the Far Western region of Nepal, including Darchula, poses a significant risk due to the prevalence of non-engineered, low-rise reinforced concrete (RC) buildings. These structures are primarily designed to withstand gravity loads with minimal or no consideration of seismic forces. A common deficiency observed is the presence of weak ground stories, often used for commercial purposes, which result in a pronounced soft-story effect that substantially increases their vulnerability to earthquake damage.

This study’s findings reveal critical structural deficiencies in non-engineered RC buildings, with model NERcA exhibiting the lowest lateral capacity and earliest onset of failure. Notably, plastic hinges were observed to form prematurely in columns rather than beams, violating the strong column–weak beam design principle and highlighting poor construction practices. Fragility analysis further quantifies this vulnerability, demonstrating that these buildings have a high probability of reaching damage states at relatively low spectral displacement values. The steep slopes of fragility curves for slight and moderate damage emphasize their susceptibility even under moderate seismic demands.

These structural weaknesses are exacerbated by the use of low-quality construction materials, lack of seismic detailing, and widespread non-compliance with relevant building codes, collectively elevating the seismic risk in the region. To reduce collapse risk and enhance resilience, the implementation of practical seismic retrofitting strategies—such as RC jacketing, steel bracing, and improved joint detailing—is critical. Additionally, stricter enforcement and adaptation of modern seismic codes are urgently needed, especially in remote, earthquake-prone areas where construction oversight is limited.

It is important to recognize the limitations of the current study. The nonlinear static pushover analysis employed is deterministic and does not capture the variability inherent in seismic ground motions, including frequency content, duration, and site-specific effects. As a result, the fragility curves developed do not incorporate uncertainties related to record-to-record ground motion variability. We explicitly acknowledge this limitation and recommend that future research incorporate Incremental Dynamic Analysis (IDA) or other probabilistic dynamic methods to provide a more comprehensive and robust assessment of seismic vulnerability.

Conflict of Interest

Authors declare that no conflict of interest.

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