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# A Case study of Building Damage Pattern in Nepal: Insights from the Nov 3, 2023 Jajarkot Earthquake

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**Abstract**

The Federal Democratic Republic of Nepal is situated in the Himalaya, one of the world's most active zones of continental collision, where there is a significant likelihood of earthquakes. The historical records of the Himalayan arc contain several reports of devastating earthquakes. Research shows that the mid-western and eastern region of Nepal has the higher seismic hazard whereas the southern regions of the country have the lowest seismic hazard. Jajarkot and Rukum West district which were most affected areas due to recent November 3 earthquake lie in mid-western part of Nepal. The Nov 3, 2023 Jajarkot Earthquake of Magnitude 6.4 in 26,557 households fully damaged and 35,455 households partially damaged. 154 individuals have perished, and 364 have sustained injuries in the earthquake that struck Jajarkot. During field inspect the main cause of collapse of buildings is found as: old age and non-engineering buildings, in plane failure and out of plane failure of building, disconnection of joint between stone mud and wood and failure of corner of building. During earthquake reconstruction, the utilization of local quality standards and adherence to national building codes and measurement criteria has been observed as essential. Enforcing code compliance and involving expert engineers in all stages of building design is crucial, as the majority of collapsing structures were not engineered. It is important that appropriate seismic design, good-quality construction materials and approved construction methods are used to minimize damage to engineered buildings.

***Keywords:*** Flexural, in plane, RC frame, Masonary

## 1. Introduction

The Federal Democratic Republic of Nepal is situated in the Himalaya, one of the world's most active zones of continental collision, where there is a significant likelihood of earthquakes. The historical records of the Himalayan arc contain several reports of devastating earthquakes. Of them, two happened in the Nepal Himalaya: the 1934 Bihar-Nepal Earthquake and the 2015 Gorkha Earthquake, magnitude 7.6 (Mw 7.8). Nepal is characterized by three major fault systems—the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Himalayan Frontal Thrust (HFT)—along with numerous smaller faults, totaling ninety-two, across the country's limited width (Parajuli et al., 2021). The mid-western and eastern region of Nepal has the higher seismic hazard whereas the southern regions of the country have the lowest seismic hazards (Chaulagain et al., 2015). Jajarkot and Rukum West district which were most affected areas due to recent November 3 earthquake (see figure1) lie in mid-western part of Nepal. The Nov 3, 2023 Jajarkot Earthquake of Magnitude 6.4 in 26,557 households fully damaged and 35,455 households partially damaged. 154 individuals have perished, and 364 have sustained injuries in the earthquake that struck Jajarkot.

Scientific investigations conducted across affected areas during the April 25, 2015 Gorkha earthquake prompted a comprehensive examination of the construction and damage characteristics inherent in five prevalent building types in Nepal: reinforced concrete (RC) frame structures, rubble structures, brick-wood structures, raw soil structures, and historic brick-wood structures (Sun & Yan, 2015).

The April 25, 2015, Gorkha Earthquake in Nepal damaged 700,000 buildings, with 96% being masonry and 4% reinforced concrete with masonry infill (Guragain et al., 2017). Similar studies shows that compared to RCC building unreinforced random rubble and abode buildings account for around 95 % of the damage caused by the earthquake in Nepal (Gautam et al., 2015).

Key findings indicate that masonry buildings primarily suffered corner separation, diagonal cracking, out-of-plane failure, in-plane flexural failure, and delamination. Non-engineered reinforced concrete buildings faced soft-story damage, joint failure, lap splice issues, column shear failure, beam failure, and infill wall failure (Guragain et al., 2018) . Most of the houses were constructed with local masons without proper supervision from technical manpower (Liu et al., 2021) . Several construction and structural deficiencies are the primary contributors to building failure (Gautam et al., 2016). Majority of the damaged buildings were not designed or constructed in compliance with the national building codes of Nepal (Sharma et al., 2016) (Rai et al., 2017).

A field reconnaissance was carried out from November 6 to 15 in the earthquake-affected regions of Jajarkot and Rukum West, focusing on various municipalities, namely Bheri, Kuse, Chhedagad, Sani Bheri, Chaurjahari, and Musikot. We observed seismic damage on building structures in highly affected areas and other areas impacted by earthquake.

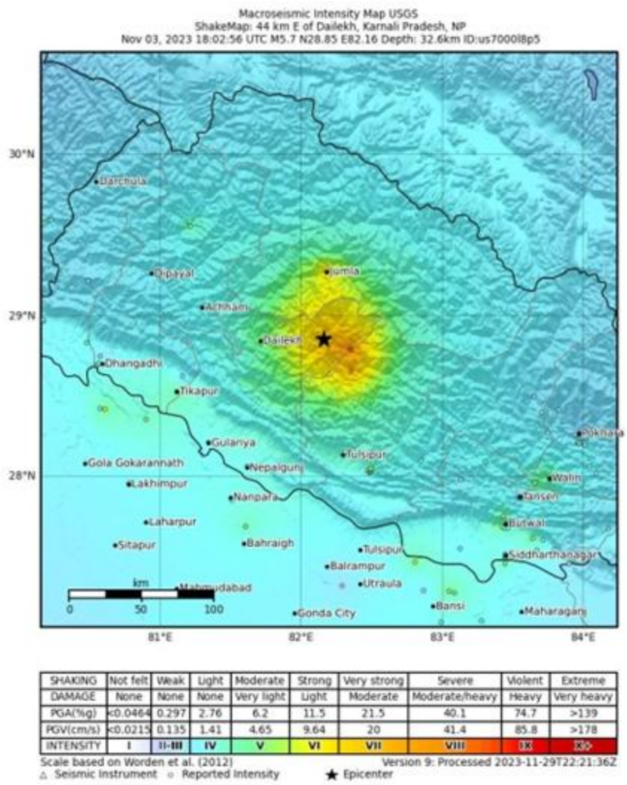


**Figure 1:** Seismic intensity map (Source: United States Geological Survey).

## 2. Damage Patterns of Building

According to National Population and Housing Census 2021, there are 366,255 households in Karnali Province which accounts for 83.1% of mud bonded bricks/stone types of foundation in building. Jajarkot accounts for 95.6 % of Mud bonded bricks/stone type of foundation and West Rukum 90.9 %. The past earthquake also shows that such types of buildings were severly affected and the figure 2 and 3 shows that most of the buildings in Karnali Province are vulnerable.

### 2.1 Unreinforced Stone Masonry Building

Most of the buildings in the badly affected areas were made of unreinforced stone masonry which suffered high degree of damage. The buildings were made of round stones directly collected from the river and such stones lack bonding and are unstable units. Less resistance to withstand to lateral force effect during Earthquake leads both out of plane and in plane failure of building.

### 2.2 Mud-wooden building

Other buildings consisting mud stone in the district are also badly affected areas were made of mud, wood which are suffered with high degree of damage. The buildings were made up of wooden joist without any band and directly collected from the forest those are weak in hilly areas to resist gravity and lateral loads; also known as unstable units. Mainly the joint between wood and mud are not created as rigid node thus whole building undergoes collapse during Earthquake.

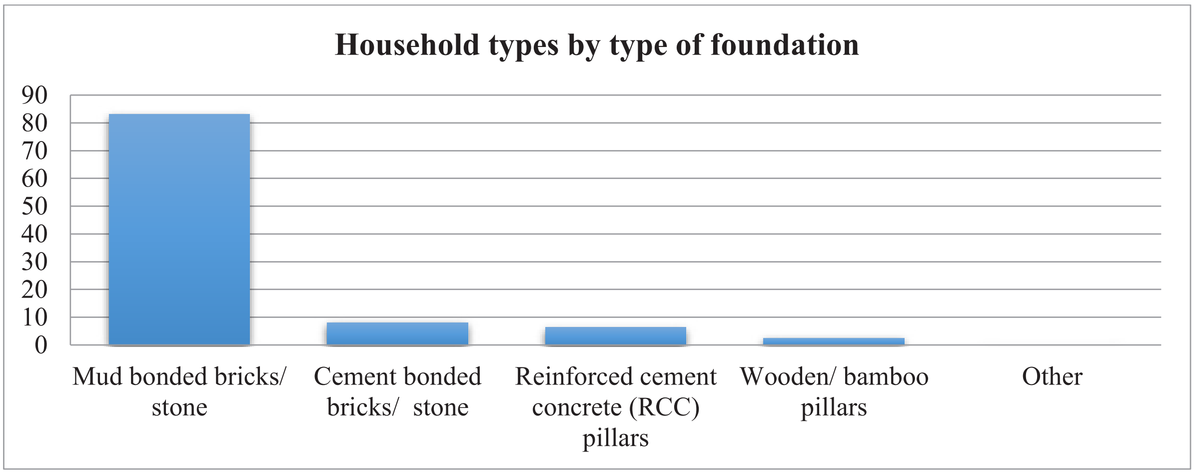


**Figure 2:** Household types in Karnali Province.

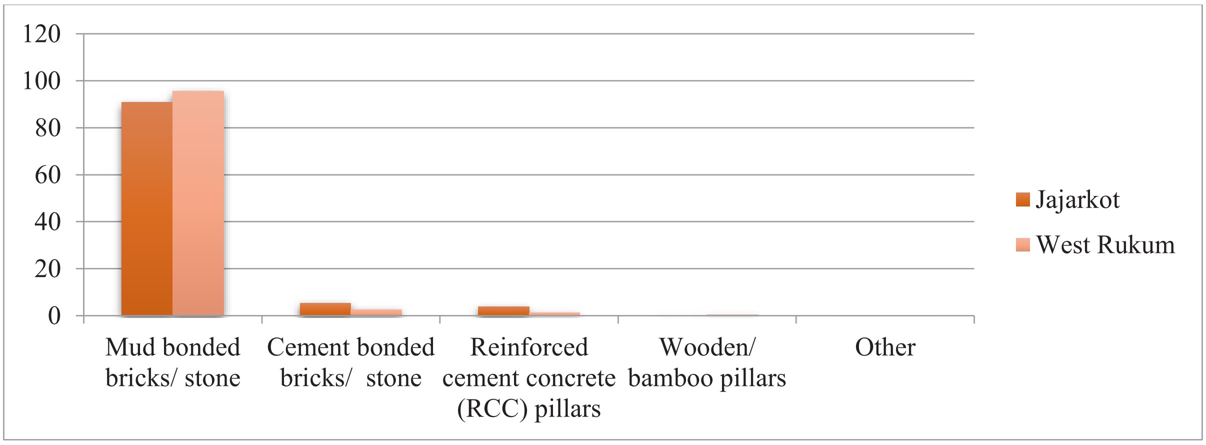


**Figure 3:** Household types in Earthquake affected districts.

### 2.3 Damage to historic Palace:

The earthquake has damaged historic palace known as “Jajarkot Durbar” as shown in figures 4, 5, 6 and 7. The bands provided in the palace prevented it from complete collapse. It was built in 1769 AD by the King of Jajarkot Hari Shah. Originally it was seven storey and reduced to four storey due to the 1934 earthquake. The April 25 Earthquake in Nepal further damaged the palace.

**Figure 4:** Diagonal crack near sill level

**Figure 5:** Flexural crack

**Figure 6:** Flexural crack

**Figure 7:** Diagonal crack

### 3. Results and Discussion

During field inspection, the damage was seen devastating in unreinforced masonry buildings and minor cracks and wall failures were observed in Reinforced Concrete Building. The main cause of collapse of buildings is found as:

i) Old age and non-engineering buildings.
ii) Heavy gable and roof construction
iii) In plane failure and out of plane failure of building
iv) Disconnection of joint between stone, mud and wood
v) Failure of corner of building

Those building which are collapsed 90 % of their components will cost severely high if retrofit process is conducted. But for those building with some diagonal cracks may be retrofitted with proper bands of RCC.

## 4. Conclusions

During earthquake reconstruction, the utilization of local quality standards and adherence to national building codes and measurement criteria has been observed as essential. Enforcing code compliance and involving expert engineers in all stages of building design is crucial, as the majority of collapsing structures were not engineered. It is noted that compliance with these standards is crucial for rebuilding both at the local and national levels. Additionally, awareness among the general public about the technical aspects and support from trained professionals and technicians are deemed necessary for earthquake-resistant house construction. It is important that appropriate seismic design, good-quality construction materials and approved construction methods are used to minimize damage to engineered buildings.

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# Structural Robustness of Steel Structures under Exceptional Event: Column Loss Scenario

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**Abstract**

Structural robustness ensures the safety and integrity of buildings under unforeseen events such as natural disasters or deliberate attacks. This study investigates the behavior of moment-resistant and pinned joint braced steel structures subjected to the extreme column loss scenario, aiming to identify structural requirements for robust design. The reference building in Brussels is a multi-story office building with ductile joints and restrained supports designed according to Eurocode provisions. Using geometrical and material nonlinear analysis, the behavior of the structure is examined under static loss of a column, with contributions from secondary frames and 3D effects included. The alternative load path method is employed, and analyses are conducted using CEPAO software to account for plastic hinges, second-order effects, and buckling. The findings highlight that while column location influences the structural response, the presence of moment-resistant connections, secondary beams, and catenary action significantly enhances robustness. These insights provide valuable guidance for engineers in designing more resilient steel structures against exceptional events.

***Keywords:*** *Robustness, Steel Structure, Moment Resistant frame, Pinned joint, Column loss*

## 1. Introduction

Steel frames are widely used in commercial and civil buildings for their ease of construction and strong load-bearing capabilities. However, when these buildings face unexpected stresses during their lifespan, certain steel columns may suffer initial damage. These localized failures can then spread throughout the entire structure, potentially leading to its collapse (Zhang *et al.*, 2020). Framed steel structures are widely used as load-bearing systems in residential, office, and industrial buildings, as well as various supporting structures. Recent events such as natural catastrophes or terrorist attacks have highlighted the necessity to ensure the structural integrity of buildings under an exceptional event (Huvelle *et al.*, 2015). While frame systems are generally designed to meet ultimate and serviceability limit states under normal conditions, accidental scenarios like vehicle impacts, explosions, or terrorist attacks may exceed these design limits (Kukla and Kozlowski, 2023). According to Eurocodes and some other national design codes, the structural integrity of civil engineering structures should be ensured through appropriate measures, but in most cases, no precise practical guidelines for achieving this goal are provided (Huvelle *et al.*, 2015).

Robustness is a critical property of structural systems, ensuring public confidence in infrastructure by maintaining safety and functionality even when unforeseen events occur. Over the past century, the importance of designing structures capable of withstanding exceptional incidents has gained significant attention, making structural robustness a key area of research. Various design codes incorporate robustness requirements; however, simple yet accurate methods for practical assessment of building robustness remain scarce, even for static structural behaviour (Comeliau, Rossi and Demonceau, 2012).

This paper examines the behaviour of steel structures in response to the unexpected loss of a column, with a primary focus on the structure's static behaviour. Firstly, it presents the overarching philosophy and strategies for establishing design requirements. It will then discuss the findings from a parametric study of these structures. Moment-resistant and pinned-joint braced multi-storey steel structures are considered for evaluation of structural behaviour.

## 2. General philosophy and adopted strategy

In recent decades, extensive research has been conducted on the collapse mechanisms of steel frames following column loss. However, due to the complex interactions among structural members during collapse, fully understanding the behavior of the entire frame remains challenging. To address this, researchers have adopted reduced models, often simplifying or neglecting the concrete floor system, to assess the robustness of steel frames under column loss (Stylianidis *et al.*, 2016) (Jiang *et al.*, 2018) (Li *et al.*, 2018). This study focuses exclusively on frames composed of columns and beams, deliberately neglecting the potentially beneficial effects of slabs in the analysis. When a frame experiences the loss of a column, the structure can be divided into two parts: the directly affected part and the indirectly affected part (Jean-François Demonceau, 2008)(Huvelle, Jaspart and Demonceau, 2014).

The *directly affected part* includes all beams, columns, and beam-to-column joints surrounding the lost column (see Figure 1). In contrast, the *indirectly affected part* encompasses the remaining structure, including the lateral portions and the stories beneath the lost column.

When a column is lost (e.g., column AB in Figure 1a), the evolution of the axial force $N_{AB}$ in the column versus the vertical displacement $u$ at its top progresses through three distinct phases, as depicted in Figure 1.

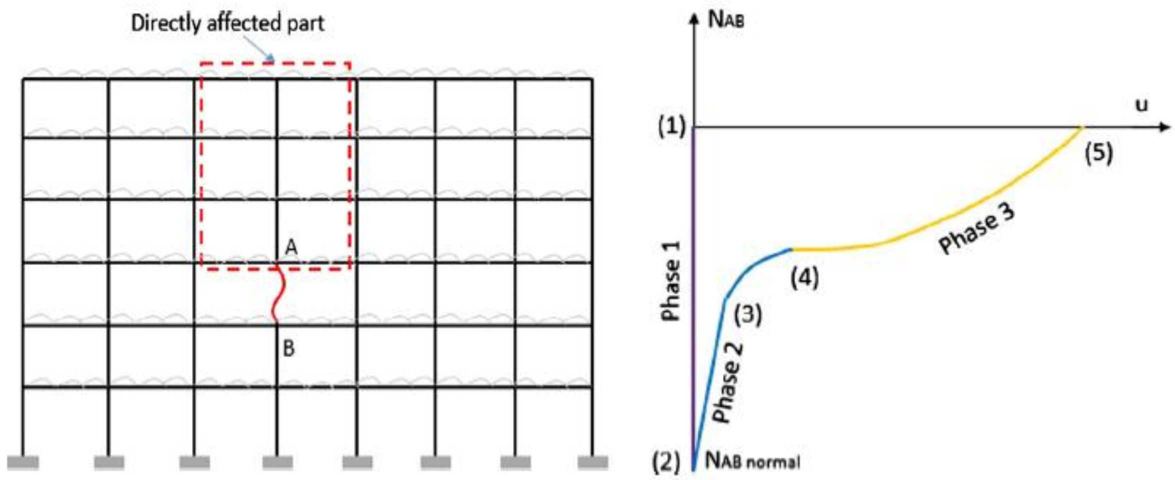
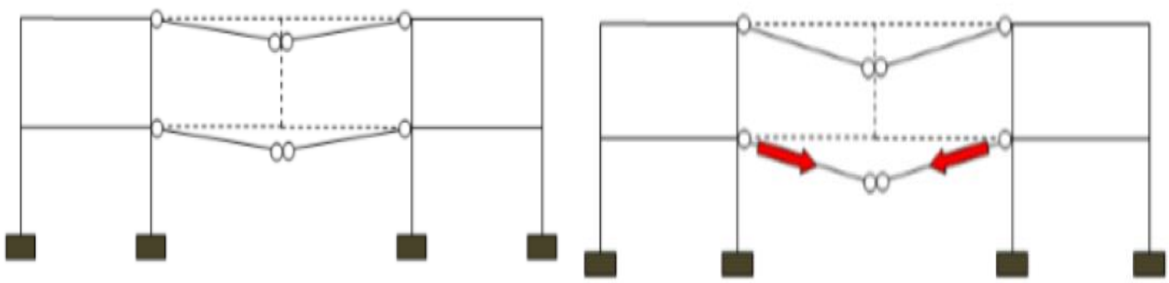



**Figure 1:** Behaviour of a frame submitted to a column loss (Huvelle *et al.*, 2015)(Jean-François Demonceau, 2008).

*Phase 1 (Pre-event: from Point (1) to Point (2) in Figure 1b)*

Before the event, the column operates under normal loading conditions, supporting loads transferred from the upper stories. This load is denoted as $N_{ABnormal}$.



(a) (b)

**Figure 2:** (a) Phase 2, and Phase 3 (Huvelle, Jaspart and Demonceau, 2014)

*Phase 2 (Column failure: from Point (2) to Point (4) in Figure 1b)*

This phase begins at the moment of the event when the column gradually loses its axial resistance. Concurrently, a plastic mechanism develops in the directly affected part of the structure. Each change in the slope of the curve in Figure 1b corresponds to the formation of a new plastic hinge in the directly affected part, culminating in a complete plastic mechanism at Point (4).

*Phase 3 (Post-mechanism: from Point (4) to Point (5) in Figure 1b)*

Once the plastic mechanism is fully developed, the vertical displacement at the top of the lost column increases significantly as the structure loses first-order rigidity. During this phase, catenary actions progressively form in the beams of the directly affected part, providing second-order stiffness to the structure. The indirectly affected part plays a crucial role by offering lateral anchorage for these catenary actions. Greater lateral stiffness in the indirectly affected part leads to stronger catenary actions in the directly affected part. Conversely, if the indirectly affected part has no lateral stiffness, catenary actions will not develop, and Phase 3 will not occur.

The behavior of the structure from Point (2) to Point (5) in Figure 1b can be predicted using the simulation shown in Figure 2. In this simulation, the frame—without the lost column AB—is subjected to a concentrated downward load *P* applied at Node A.

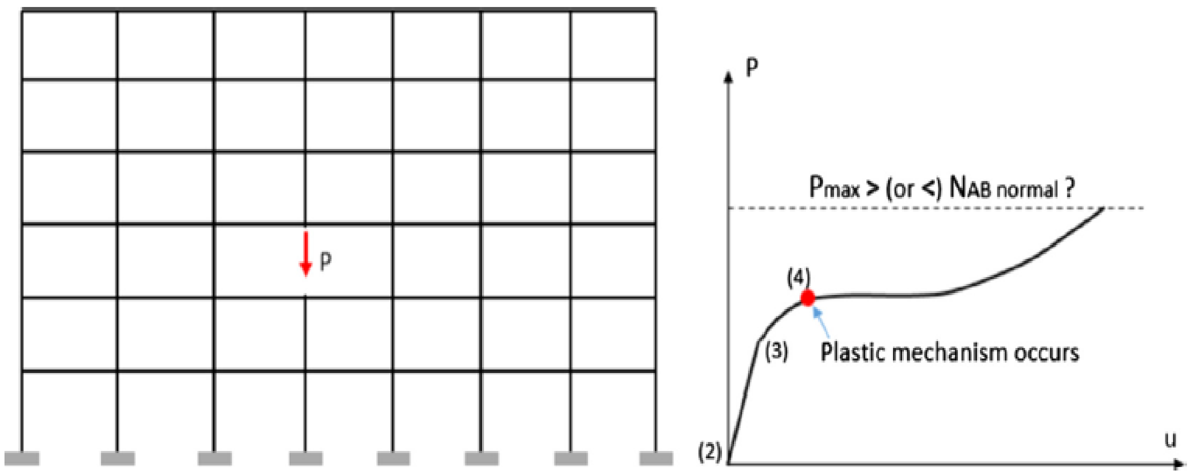


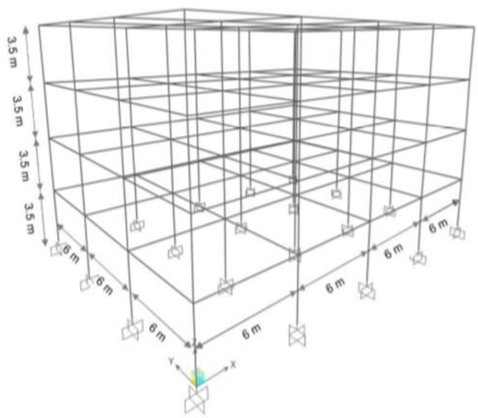

**Figure 3:** Simulation of column loss (Huvelle *et al.*, 2015).

The analytical method developed in Liège aims to derive a *P*–*u* curve that characterizes the behavior of the simulated structure (see Figure 3), estimate the redistribution of loads during these phases, and determine whether the structure can reach Point (5) (i.e., when $P$=$N_{ABnormal}$. Achieving this point indicates that the damaged structure possesses sufficient resistance and ductility to sustain the large displacements and associated forces arising from the activation of alternative load paths (Huvelle *et al.*, 2015).

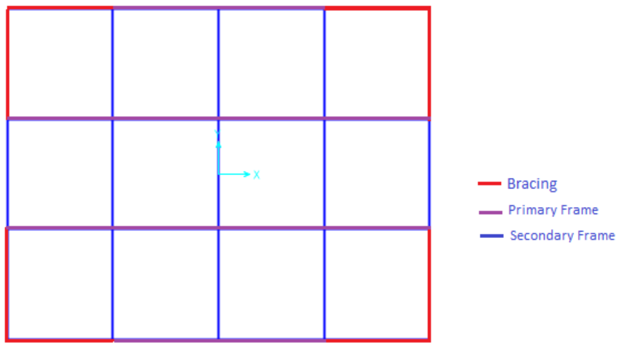
## 3. Structural response under column loss

### 3.1 Geometry configuration of the structure

The reference building selected for this analysis is a four-story office building located in Brussels, Belgium. The choice of this type building was predicated on its alignment with the study's principal aim: to assess structural responses in scenarios involving column loss. Office buildings were specifically chosen due to their typical high occupancy and heightened susceptibility to disproportionate collapse following unexpected incidents such as accidental impacts, explosions, or extreme loading conditions. This renders them pivotal cases for evaluating structural resilience. Moreover, office buildings commonly exhibit open-plan layouts with fewer structural redundancies, thereby amplifying their vulnerability in scenarios involving column loss. The building features a structural layout consisting of four spans in the X-direction, each with a span length of 6 meters, and three spans in the Y-direction, also with a span length of 6 meters. Each story has a height of 3.5 meters, as illustrated in Figure 4.




(a)

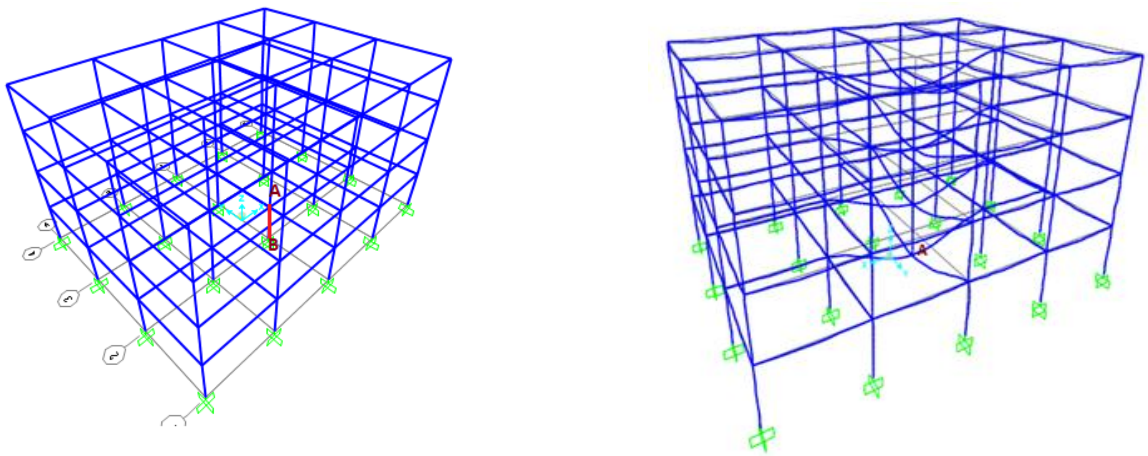



(b)

**Figure 4:** (a) Reference 3D-Steel Structure of Office Building, and (b) Plan view of the 3D structure

The reference structure is designed and analysis with SAP2000 as per EN1991-1-1 (European Committe for Standardisation, 1994), without considering the seismic effect, with fully moment-resistant and ductile joints supported by restrained connections, ensuring adequate rotational capacity. However, verifying the structure's sufficient ductility to accommodate the maximum deflection required to develop catenary action without failure is essential. The structural design complies with the provisions of the Eurocode (EN 1990) (McKenzie, 2013), meeting the requirements for ultimate and serviceability limit state checks. The material used is mild steel grade S355 according to EN10025 (European Committee for Standardization, no date) with elastic-perfectly plastic behaviour. Figures 5 and 6 show the structural models of moment-resistant and pinned-joint structures in SAP2000 before and after the column loss.

During the structural analysis and verification of structural members using SAP2000, the composite action between the concrete slab and steel beams was not considered. Secondary beams were assumed to be continuously supported and pinned. The secondary beams are positioned between the primary beams, spanning across the four-story office building's three-span (Y-direction) and four-span (X-direction) layout. They are oriented perpendicular to the primary beams, ensuring effective force redistribution across the structure. These beams contribute significantly to load-sharing mechanisms in both moment-resistant and pinned-joint braced structures. The moment-resistant structure utilized IPE270 for external frames and IPE360 for internal frames, conforming to Eurocode standards. Similarly, the pinned joint structure employed IPE360 for external frames and IPE450 for internal frames. Column sections included HE320B, HE240B, HE220B, HE200B, HE180B, HE160B, and HE140B, with bracing provided by IPE120, all verified according to relevant standards.



(a) (b)

**Figure 5:** Moment resistant structure: a) Structure before column loss, and b) Structure after column loss

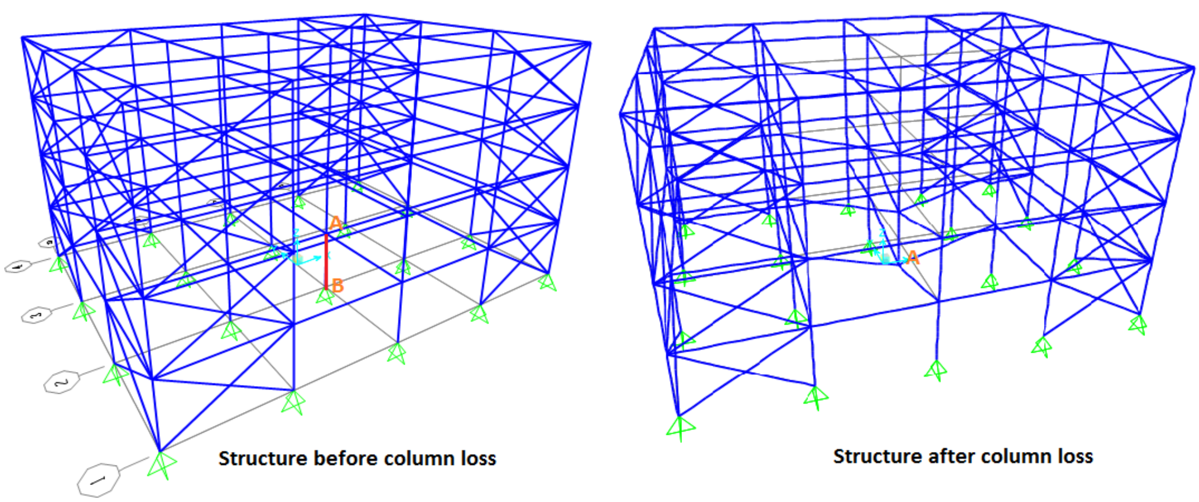



**Figure 6:** Pinned joint structure before and after column loss

### 3.2 Methodology

The design approach outlined in the section general philosophy and adopted strategy is employed to study the redistribution of forces in the structure during the static loss of a column. The investigation is performed using a geometrical and material non-linear analysis. The alternative load path method is applied according to EN 1991-1-7 (EN 1991-1-7, 2006), considering elasto-plastic behavior and second-order effects. The study employs the CEPAO program, developed by the University of Liège's Department of Structural Mechanics and Stability, a comprehensive tool for the automated analysis and design of frame structures (Dang Hung, 1984), to perform a geometrical and material non-linear analysis of the moment-resistant and pinned-joint braced steel structures under a column loss scenario. Initially designed by Nguyen-Dang Hung (Dang Hung, 1984), it provided a unified approach for 2D frame structures, incorporating elastic analysis, rigid-plastic limit analysis with proportional loading, step-by-step elastic-plastic analysis, shakedown analysis under variable repeated loads, and optimal plastic design with stability checks and discrete profile selection (Van Long and Dang Hung, 2008). Over time, CEPAO has evolved to support space steel frames, integrating rigid-plastic analysis and design through linear programming (LP) and elastic-plastic analysis using step-by-step methods, considering both first and second-order effects (P-delta) (Van Long and Dang Hung, 2008) (Long and Hung, 2010). The program employs classical finite element methods combined with LP, enabling precise calculations of ultimate load capacity, bending moment distribution, axial and shear forces, and structural collapse mechanisms. CEPAO remains a powerful and evolving tool for structural analysis and optimization, offering advanced capabilities for engineers designing resilient and efficient frame structures (Van Long and Dang Hung, 2008) (Long and Hung, 2010) (Hoang *et al.*, 2015) (Li, 2008).

The main roles of CEPAO in this study are to simulate the progressive collapse response of the structure, incorporating the Plastic hinge formation to capture the redistribution of internal forces, Second-order (P-$\Delta$) effects to account for instability due to large deformations, buckling analysis to evaluate local and global stability under exceptional loads. In addition to this, the software applies the Alternative Load Path Method to assess structural robustness after the sudden removal of a column and the analysis determines the load factor ($\lambda$) vs. vertical displacement relationship, identifying critical points where plastic hinges, catenary action, and collapse occur. Following assumptions are made during the CEPAO simulations;

i. Elasto-plastic material behavior: The structural elements follow an elastic-perfectly plastic stress-strain relationship (S355 steel as per EN 10025).

ii. Idealized beam-to-column connections:

- Moment-resistant structure: Fully ductile joints with rotational capacity.
- Pinned-joint braced structure: Hinged connections allowing free rotation.

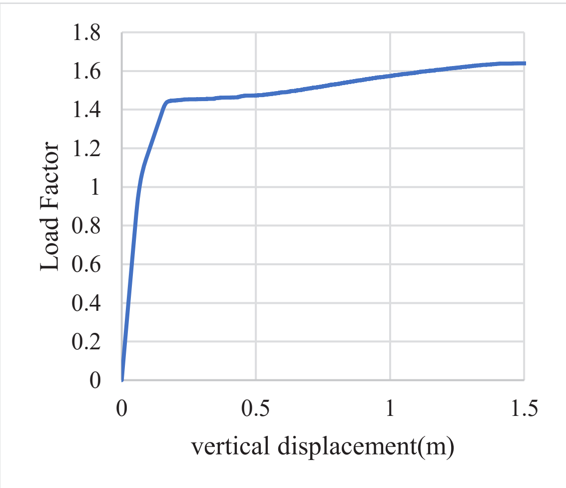
iii. Horizontal bracing system used in place of the concrete slab: Since the real structure lacks horizontal bracing, CEPAO introduces a strong, stiff horizontal bracing system to maintain numerical stability in the absence of diaphragm action.

iv. Load application: The removed column's initial axial force is applied as a downward load (P) at the column location to replicate real-world load transfer.

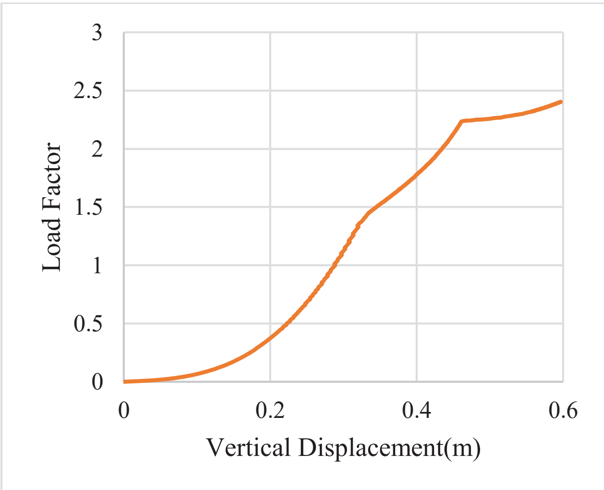
The methodology follows Eurocode EN 1991-1-7 (EN 1991-1-7, 2006), ensuring compliance with standardized robustness assessment frameworks. CEPAO has been validated against experimental tests and analytical models in prior research (Van Long and Dang Hung, 2008) (Long and Hung, 2010) (Hoang *et al.*, 2015), including PhD studies at the University of Liège (Li, 2008).

### 3.3 Static Behaviour of the Structure

This section investigates the static behavior of the structure following the loss of a column. The structure's robustness is evaluated based on its global stability during the numerical analysis. The study emphasizes the role of catenary action and load redistribution in enhancing the robustness of moment-resistant and pinned-joint braced steel structures under a column loss scenario. If the structure remains stable until a load factor $\lambda$=1 (representing the complete loss of the column), it is deemed robust. Figure 7 presents the evolution of the vertical displacement at the top of the lost column A as shown in Figures 5 and 6 respectively as a function of the load factor $\lambda$ under accidental limit state load combinations.




(a)




(b)

**Figure 7:** Vertical displacement at the top of the failing column versus load factor, (a) Moment resistant structure, and (b) Pinned Joint structure

After the loss of a column, the structure undergoes a progressive redistribution of loads from the directly affected area to adjacent structural members. The load factor (λ) exceeding 1 across all column loss scenarios confirms the sufficient redundancy of the structure. Load redistribution is primarily facilitated by two key mechanisms, Flexural behavior (Phases 1 & 2), Initial redistribution occurs through beam bending, with plastic hinges forming at beam ends and Catenary action (Phase 3): as displacement increases, axial tension in beams activates catenary forces, further stabilizing the structure.

***Flexural Behavior***

This behavior is primarily associated with the bending of beams in the directly affected region and serves as the dominant mechanism during Phases 1 and 2.

*Phase 1: Elastic deformation*

The development of plastic hinges is a fundamental aspect of the analysis, as it indicates the redistribution of loads following a column removal. During the first phase, the structure behaves elastically. A plastic hinge forms at the joint when the moment at the beam ends reaches the resistance moment of the joint, which is lower than the plastic moment of the beam. The elastic stage ends at a load factor $\lambda$=0.80 for moment-resistant structure (see Fig. 7a). Similarly, the structure remains within its elastic limit until $\lambda$ = 1.30, where the first yielding occurs in the beam directly above the lost column due to tension in pinned joint structure (see Fig. 7b). Up to this point, the structure maintains its initial stiffness, and no permanent deformations are observed.

*Phase 2: Plastic deformation*

Beyond $\lambda$=0.80 in the case of moment-resistant structure, plastic hinges begin to form quasi-simultaneously on all floors. Each change in slope in the load-displacement curve corresponds to forming a new plastic hinge. At $\lambda$=1.44, the global beam plastic mechanism develops in the directly affected part of the structure, marking the start of Phase 3 (see Fig. 7a). The mechanism is completed when plastic hinges develop at the mid-span of the double beams on each floor in the directly affected area. In the case of a pinned joint braced structure, after $\lambda$ = 1.30, the structure enters the plastic deformation phase, where permanent deformations begin to accumulate. Initially, yielding spreads to beams in the directly affected part, but the structure remains stable and can still withstand additional loads. As the load factor increases further, secondary plastic hinges begin to form, and redistribution mechanisms such as catenary action become dominant.

A key aspect of the observed flexural behavior lies in the bending of the directly affected region, influenced by the interaction between the primary and secondary frames. In the 3D structure, the extended area of the directly affected region leads to the onset of the beam plastic mechanism at $\lambda = 1.44$, which is the transition point from flexural to catenary action occurs, marking the onset of significant tension in beams. Similarly, the pinned joint braced structure shows greater reliance on axial forces, activating catenary action earlier (around $\lambda = 1.30$) due to its limited moment resistance.

***Member Behavior (Catenary Action)***

This behaviour involves significant tensile forces (catenary action) developing in beams directly affected by a plastic mechanism. These effects enhance load-carrying capacity, allowing the structure to endure column loss until a complete plastic mechanism forms in the frame.

Additionally, "member behaviour" occurs when tensile forces are generated in beams directly above the lost column, influenced by both primary and secondary frames. In a 3D structure, having more beams above the lost column increases load transfer paths to indirectly affected areas, improving the structure's ability to support exceptional loads after column loss. The catenary mechanism increases the ultimate load-bearing capacity, delaying collapse even after significant deformation. This study highlights that catenary action is crucial for maintaining stability, especially in structures with limited moment-resisting capacity. Incorporating stronger beam-to-column connections and lateral restraints can further enhance load redistribution efficiency.

*Phase 3: Catenary Action and Membrane Effects*

Once the plastic mechanism forms in the directly affected area, the vertical displacement at the top of the lost column increases rapidly due to the loss of bending stiffness in the joints of both the primary and secondary frames. Tension forces develop in the bottom beam above the lost column, activating the axial stiffness of the beam. These membrane effects reduce the deformation rate until yielding begins in the indirectly affected area.

The failure mode is characterized by forming a plastic mechanism in the indirectly affected area at $\lambda = 1.64$ in moment-resistant structures (see Figure 8). Although the structure can carry additional load, it becomes unstable once the column is removed.

From graph Figure 7b, it is observed that there is a change in the slope of the curve at $\lambda = 2.233$, indicating the yielding of beams in the indirect area and the buckling of adjacent columns next to the column loss, signalling a reduction in structural stiffness. Ultimately, at $\lambda = 2.40$, the structure can no longer sustain additional load and collapses due to the yielding of the braces and beams in the indirectly affected area (see Figure 9). However, the reference structure is sufficiently robust to withstand the additional load resulting from the exceptional event of column loss. The first yielding point in the structure occurs only after the complete loss of the column.

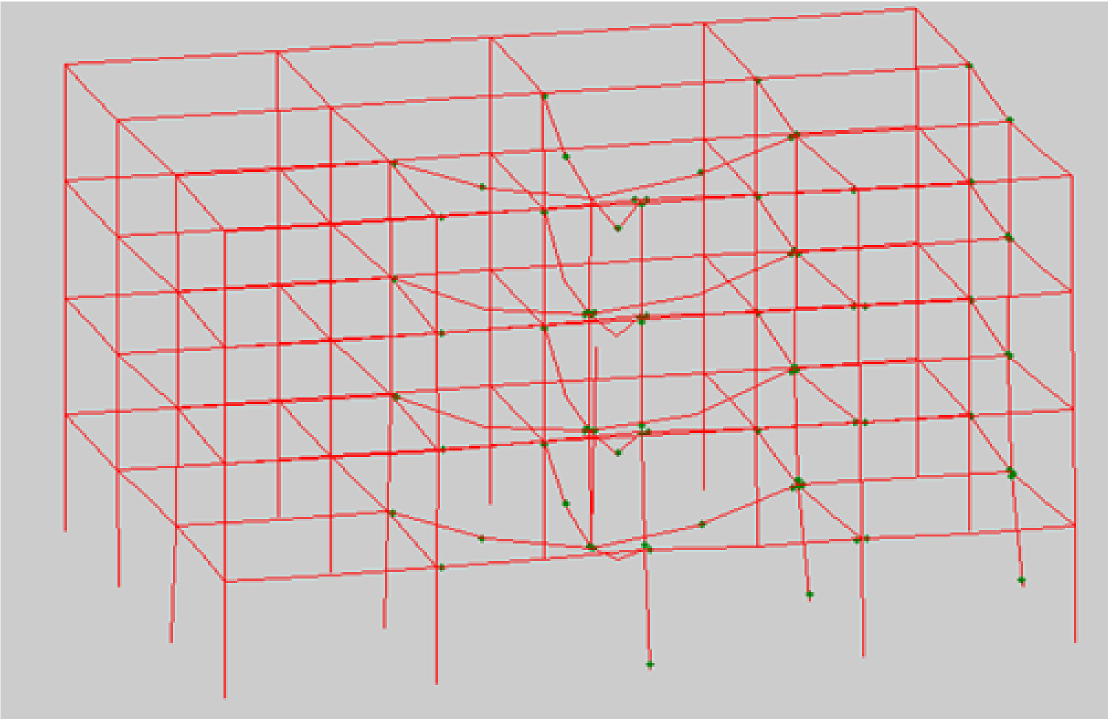


**Figure 8:** Plastic Mechanism in the indirectly affected parts.

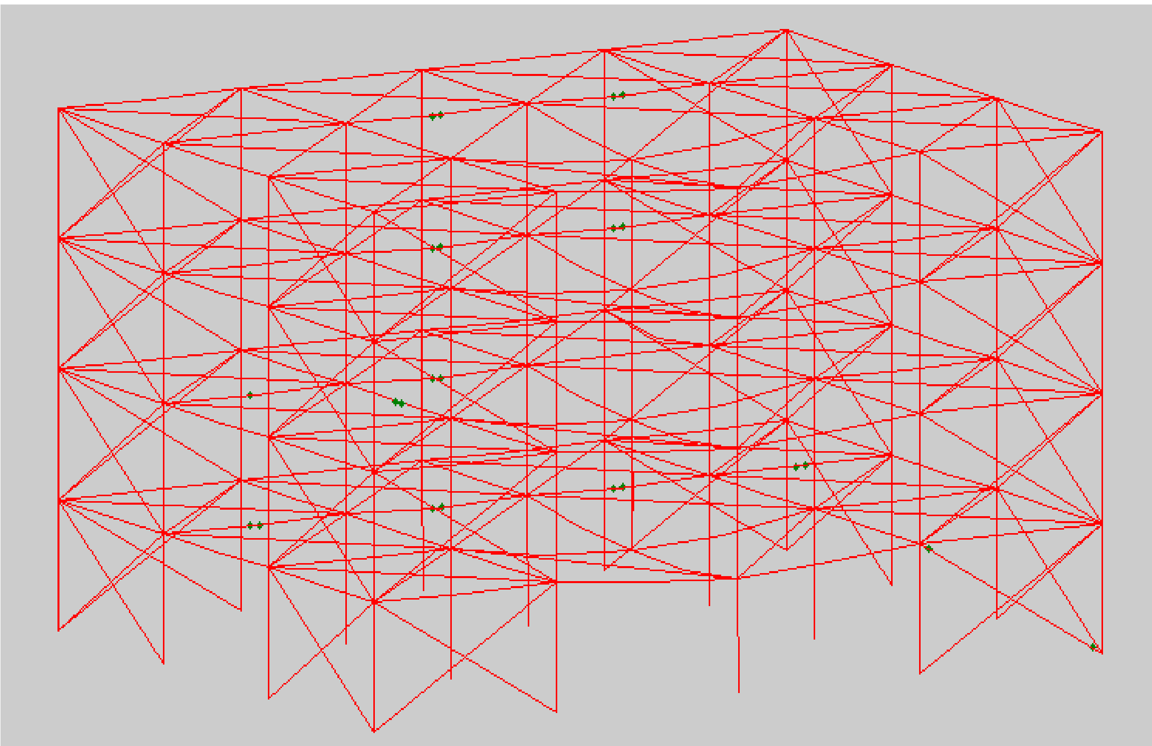


**Figure 9:** Yielding mechanism in the indirectly affected parts of structure.

### 3.4 Column Loss at Different Positions

Figures 10, 11, and 12 illustrate the structure's behaviour under the loss of columns located at different positions within the structural grid. Figure 10 highlights the positions of the columns considered for removal (Col-1 to Col-6). Figures 11 presents the corresponding load factor ($\lambda$) versus vertical displacement curves for each column loss scenario for moment-resistant structure. Regardless of the column location, the structure shows consistent behaviour, maintaining stability and sufficient load-carrying capacity. The load factor ($\lambda$) exceeds unity in all cases, confirming that the structure can withstand the complete loss of any single column without failure.

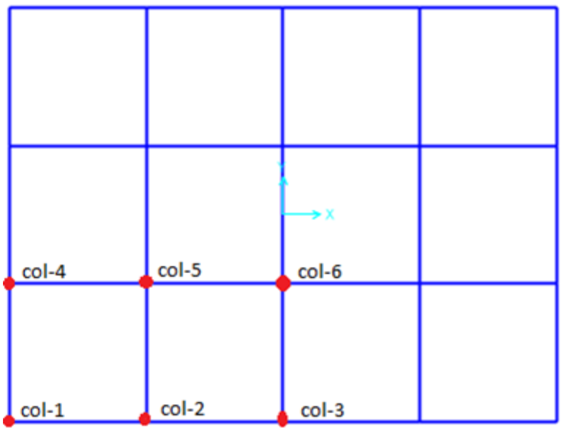



**Figure 10:** Position of column loss

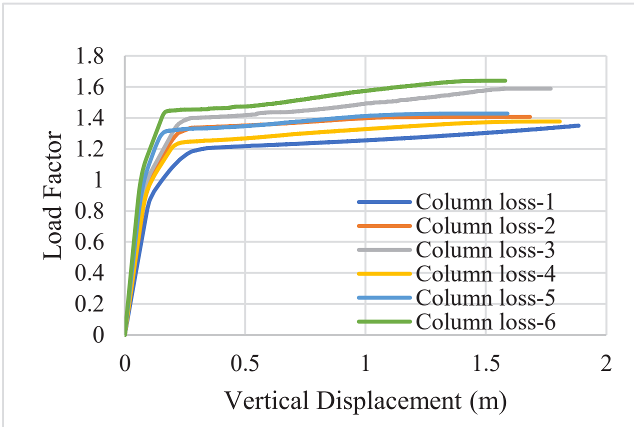
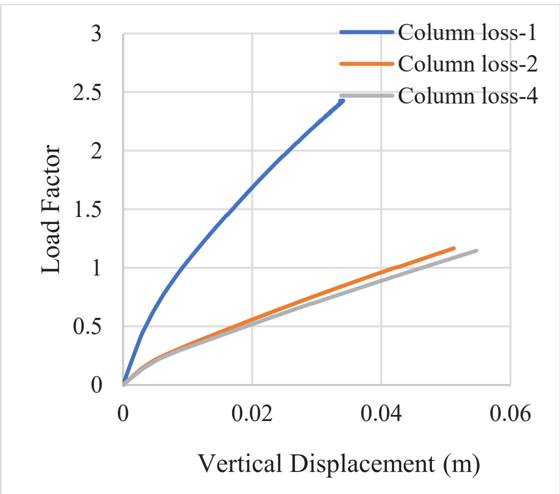



**Figure 11:** Structure behaviour after the loss of column- Moment Resistant Structure



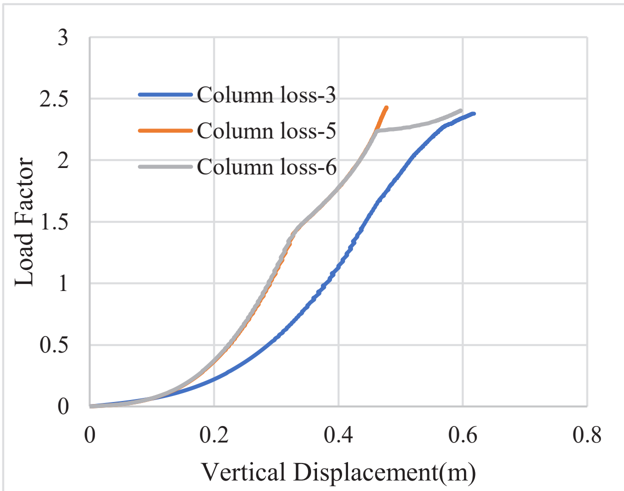




**Figure 12:** Structure behaviour after loss of column- Pinned Joint Braced Structure.

Figure 12 illustrates the structural behavior of the Pinned Joint Braced Structure under different column loss scenarios by presenting the relationship between load factor ($\lambda$) and vertical displacement at the location of the lost column. The curves in the figure 12 represent different column loss positions, highlighting the variations in structural response based on the location of the missing column. The initial phase of each curve shows a gradual increase in vertical displacement, which corresponds to elastic deformation. As the load factor increases, plastic hinges start forming, leading to a nonlinear response, with curves of column 3-5-6 loss showing steeper slopes due to higher flexibility in those specific locations. The structure shows higher displacement at lower load factors, indicating that those positions are more critical for overall stability. The load factor at which the curves flatten represents the onset of significant plastic deformation and redistribution of forces through alternative load paths. Overall, the variations in the curves reflect the influence of column position on structural response. The results demonstrate that the Pinned Joint Braced Structure remains stable beyond column removal, supporting the conclusion that it possesses sufficient redundancy to prevent progressive collapse.

The analysis demonstrates that the structure maintains global stability irrespective of the column loss position, confirming its robustness under accidental scenarios. In all cases, the load factor ($\lambda$) exceeds unity, indicating that the structure can withstand the complete removal of a column without immediate failure. While the structure remains stable, the level of deformation and the formation of plastic hinges vary depending on which column is removed. Some column loss positions result in higher displacements and earlier hinge formation, making them more critical in terms of stability. After plastic hinge formation, the structure activates catenary action, allowing tensile forces in beams to assist in load transfer. The secondary frame enhances load redistribution, particularly in cases where column loss occurs near the center of the building.

## 4. Summary

This study confirms that multi-story steel frames can effectively redistribute loads under different column loss scenarios, ensuring progressive collapse resistance. The findings highlight that while column location influences the structural response, the presence of moment-resistant connections, secondary beams, and catenary action significantly enhances robustness. These insights provide valuable guidance for engineers in designing more resilient steel structures against exceptional events.

The study highlights the critical role of catenary action in ensuring structural stability, particularly in systems with limited moment-resisting capacity. Strengthening beam-to-column connections and incorporating lateral restraints can significantly enhance load redistribution efficiency. However, practical constraints such as the availability of high-ductility steel (e.g., S355) and the quality control of welding and joint fabrication can affect structural performance under extreme conditions. Additionally, implementing alternative load paths, catenary action, and redundancy strategies increases both material and labor costs. To address these challenges, proposed solutions include the use of pre-qualified ductile connections, improved welding procedures, and stricter fabrication tolerances to ensure consistent structural behavior under unexpected loads. Optimized design approaches, such as partial-strength connections, strategically placed reinforcements, and cost-effective retrofitting techniques for existing structures, are recommended.

The study employs simplified assumptions (e.g., neglecting slab contributions and utilizing artificial horizontal bracing in CEPAO) that may not fully capture real-world structural behavior. Future research should incorporate composite slab action, realistic connection behaviors, and dynamic load effects in structural analyses to bridge the gap between theoretical frameworks and practical implementation.

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## A COMPARATIVE STUDY OF MIDDLE RISE APARTMENT BUILDING WITH DIFFERENT SEISMIC CODES


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**Abstract**

This study presents a seismic analysis of a reinforced concrete (RCC) apartment building, evaluated against various seismic codes to ensure structural safety in earthquake-prone regions. The analysis employs a finite element approach and considers different seismic parameters, including torsion, drift, displacement, and base shear. The building was modelled in ETABS, maintaining consistent horizontal and vertical configurations. Seismic analysis was conducted using the Linear Equivalent Static Method and the Linear Dynamic Response Spectrum Method. The Nepal National Building Code (NBC) - 105:1994 and 105:2020, as well as Indian Standards (IS) - 1893:2002 and 1893:2016, were utilized for designing the building structure. As compared to IS codes, NBC 105:2020 codes give higher results in base shear by 43.48%, considering the ULS method and by 37.66%, considering the SLS method for the same building used in the analysis. Nepalese code considers higher accidental eccentricity (10%) than Indian code (5%), which can result in higher torsional forces in NBC 105 designs.



**Keywords:** Response Spectrum, Drift, Tectonic Plate, Seismic Codes, Base Shear


## 1. Introduction

Earthquakes are defined as a vibration of the earth's surface that occurs after a release of energy in the earth's crust. Most earthquakes are small but are not readily felt. More significant and violent earthquakes occur in a release of energy as the plates slide past or collide with one another (Patriat and Achache, 1984). In seismically active areas, earthquakes are the main threat to civil infrastructure development. Nepal is located in a seismically active region due to its location in the subduction of the Indian plate under the Eurasian plate with an approximate subduction rate of 25-40 cm/year. Such an area is prone to weak to moderate ground shaking, causing the failure of major Civil Infrastructures like buildings, bridges, towers, roads, etc. Here, in Nepal, the damage was largely seen in residential structures in rural, mountainous areas, with over 96% of them being load-bearing structures (Adhikari and D’Ayala, 2020; Malla *et al.,* 2024).

The behaviour of a structure during an earthquake depends on the distribution of stiffness, mass, plan, strength and many other irregularities in both the vertical and horizontal direction of the structure (Ghimire and Chaulagain, 2024). Buildings with simple geometry, uniformly distributed mass, and stiffness in plan and elevation are less vulnerable compared to structures with irregular configurations (Kostinakis and Athanatopoulou, 2020). The G+5 story with consistent configuration is modelled in ETABS version 19.2. Beams and columns in moment frames are proportioned and detailed in such a manner that they must resist flexural, axial, and shearing actions that result in a building sway through multiple displacement cycles during strong earthquake ground shaking (Landingin *et al.,* 2013; Dhanvijay *et al.,* 2015; Hampshire *et al.,* 2018; Patil *et al.,* 2021).

The Nepal National Building Code (NBC) was established following the devastating earthquake in 1988, revealing significant weaknesses in Nepal's construction practices. It was officially implemented in 1994, with the primary goal of improving building safety, particularly regarding seismic resistance. The codes are periodically revised to incorporate advancements in engineering practices and lessons learned from past disasters, including the 2015 Gorkha earthquake, with the most recent update occurring in 2020. Similarly, IS 1893 is a foundational code in Indian earthquake engineering, providing guidelines for designing structures to withstand seismic forces. Since its first publication in 1962, it has been revised several times, with significant updates in 1984, 2002, and the latest in 2016, reflecting advancements in understanding earthquake dynamics and structural behaviour (IS 1893 Part 1: 2002; IS 1893 Part 1: 2020).

**Story drift**

It is the relative displacement between the floors above or below the storey under consideration (Adhikari and Poudel, 2023). These limits vary depending on the building's occupancy and function. Residential buildings typically have stricter limits. In contrast, Industrial structures may allow more flexibility. The story drift will be controlled through different mediums like shear walls, braced frames, or moment-resisting frames or incorporating Damping Systems like base isolators or tuned mass dampers, ensuring symmetry in mass and stiffness to reduce torsional effects. Understanding and controlling story drift is fundamental for ensuring structures' safety, functionality, and resilience in dynamic conditions.

**Displacement**

Displacement refers to moving a point or a structure from its original position due to applied forces, such as loads, thermal effects, or seismic activity. Determination of the story displacement is an important indicator of the building's ability to withstand seismic forces. It provides important information for the design of lateral load-resisting elements as well as the overall lateral stability of the building (Sapkota *et al.,* 2013).

**Torsion**

Torsion is generally the twisting or rotation effect produced by the forces that cause the unequal movement of the floor within the same level. The major source of torsion is eccentricity, and initial attempts should be made to minimize the eccentricity in the building. Eccentricity in the building can be minimized by Maintaining symmetry in buildings, avoiding changes in the direction of forces within a frame, not allowing the intersection of the cantilever section, and designing the structural members to withstand torsional forces/moments as per standard codes. (Ghimire and Chaulagain, 2021).

Nepal and India are in active seismic zones, where earthquakes pose significant risks to life and property. Comparing these two codes is crucial to ensure that structures in both countries are designed to withstand seismic forces effectively. Both nations have experienced devastating earthquakes, such as the Gorkha Earthquake in 2015 and the Bhuj Earthquake in 2001. By examining each code, both countries can adopt best practices and learn from each other's seismic experiences. Understanding the differences and strengths of each code can help enhance their seismic regulations, aligning them with global best practices while addressing local needs (Suliman and Lu, 2024; M. Afifi and R. Ahmed).

The aim of comparing Nepal's national building seismic codes and India's seismic codes (IS 1893) is to evaluate their similarities, differences, and overall effectiveness. The primary objective is to analyze the underlying design principles, including load assumptions, response spectrum analysis, ductility requirements, and base shear calculations. Additionally, the comparison will assess the seismic zoning maps, zone factors (Z), and ground motion parameters, such as soil types and response spectra used in both codes.
This study does have limitations; specifically, it does not create an infill model, but it does consider the weight of the wall in the analysis. The study emphasizes the importance of the evolution of seismic codes in earthquake-prone regions, yet it only compares the latest two revised editions of Indian and Nepalese codes. Furthermore, only one model is used to achieve the study's objectives.

Nepal Building Code (NBC) - 105:1994 and 105:2020, along with Indian Standard (IS) - 1893:2002 and 1893:2016, are utilized for designing building structures, while seismic parameters will be assessed based on these standards.
According to NBC 105:2020 Load Combinations for Parallel Systems are:

$1.2DL + 1.5LL$ (1)

$DL + \lambda LL \pm E$ Where, $\lambda = 0.6$ for storage facilities= 0.3 for other usage (2)

Also, from NBC 105:2020 Load Combinations for Non- Parallel Systems are:

$1.2DL + 1.5LL$ (3)

$DL + \lambda LL + (Ex \pm 0.3Ey)$

$DL + \lambda LL + (0.3Ex \pm Ey)$ (4)

Where, $\lambda = 0.6$ for storage facilities = 0.3 for other usage

As per IS 1893: 2016 the structure should be designed for the given load combinations

$\pm EL_X \pm 0.3\ EL_Y\}]$ and (5)

$\pm 0.3EL_X \pm EL_Y\}]$ (6)

where X and Y are two orthogonal horizontal plan directions. Thus, EL in the load combinations given above shall be replaced by ($EL_X \pm 0.3\ EL_Y$) or ($EL_Y \pm 0.3\ EL_X$). Hence, the sets of load combinations to be considered shall be as given below:

$1.2[DL+IL\pm[\{\ EL_X \pm 0.3\ EL_Y\}]$ and (7)

$1.2[DL+IL\pm[\{\ EL_Y \pm 0.3\ EL_X\}]$; (8)

$1.5[DL\pm[\{\ EL_X \pm 0.3\ EL_Y\}]$ and (9)

$1.5[DL\pm[\{\ EL_Y \pm 0.3\ EL_X\}]$; (10)

$0.9[DL\pm1.5[\{EL_X \pm 0.3\ EL_Y\}]$ and (11)

$0.9[DL\pm1.5[\{EL_Y \pm 0.3\ EL_X\}]$ (12)

## 2. Materials and Methodology

### 2.1 Building configuration

The model used for comparison is the same for all seismic codes, and the salient features of the building are described below in tabular form.

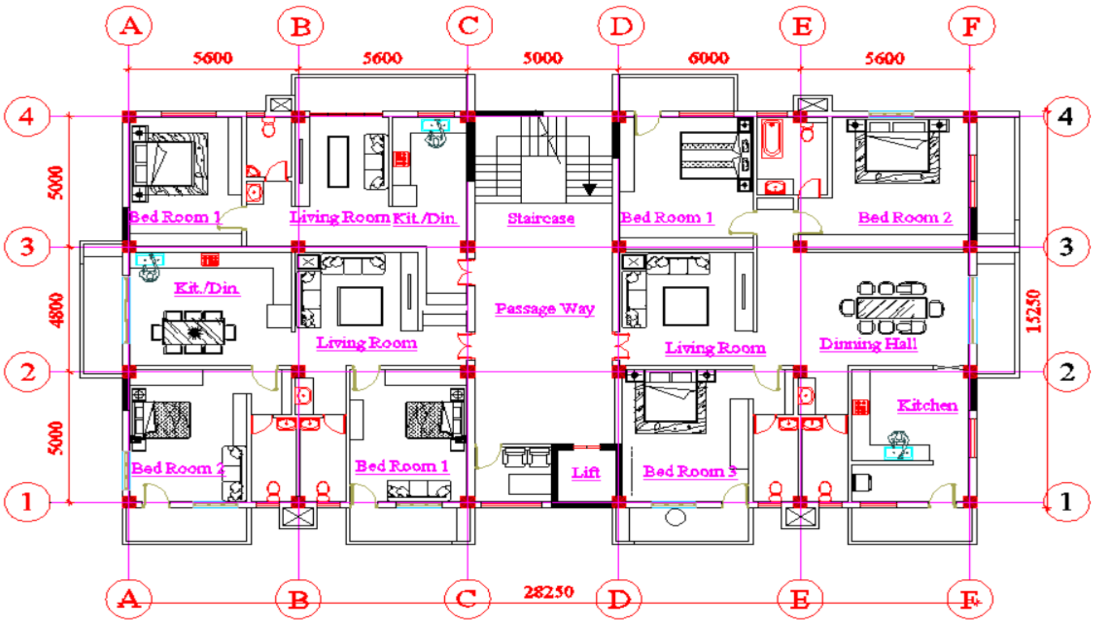



**Figure 1:** Architectural Drawing of Ground Floor.

**Table 1:** Description of Building (NBC 206:2015, Architectural Design Requirements).

| Parameters | Details |
|---|---|
| Types of Building | Apartment Building |
| Category of Building | Mid-Rise Building |
| Structural System | RCC Frame Structures; SMRF |
| Number of Story | 6 (G + 5 + Staircase Cover) |
| No. of Bays in X Direction | 5 nos. of Bays |
| No. of Bays in Y Direction | 3 nos. of Bays |
| Plint Area | 430.8125 Sq m |
| Floor Height | 3.05 m |
| Size of Building | Length = 28500 mm, Breadth = 15250 mm |
| Grade of Concrete | M25 for Beam, Column and Slab |
| Grade of Steel | Fe 500 |
| Type of Slab | Two - way Slab |
| Type of Beam | Rectangular main Beam |
| Type of Column | Rectangular Column |
| Type of Foundation | Mat Foundation |
| Type of Stair-case | 3$^{rd}$ Quarter Landing Type |
| Method of Analysis | Static and Dynamic |

## 2.2 Material

**Table 2**: Parameters used for the design of models (IS 456:2000, Indian Standard Code of Practice for Plain and Reinforced Cement Concrete).

| Description | Section/Constant | Units |
|---|---|---|
| Parameters | Data | Unit |
| Column size | 500X500 | mm X mm |
| Main Beam size | 300X500 | mm X mm |
| Secondary Beam size | 250X400 | mm X mm |
| Slab thickness | 125 | Mm |
| Shear wall | 200 | Mm |
| Specific weight of concrete | 25 | $KN/m^3$ |
| Unit weight of Brick | 19.2 | $KN/m^3$ |
| Modulus of elasticity of concrete | 25000 | MPa |

## 2.3 Modelling of Buildings

Modelling is done using ETABS 2000 Vs. 19.1, using the finite element model of a building. Modelling is done as per the architectural drawing, and the changes are made later as per the structural requirements. Special attention is given while modelling the building in ETABS as a very small and unnecessary section may cause the failure of the whole structure which is undesirable.

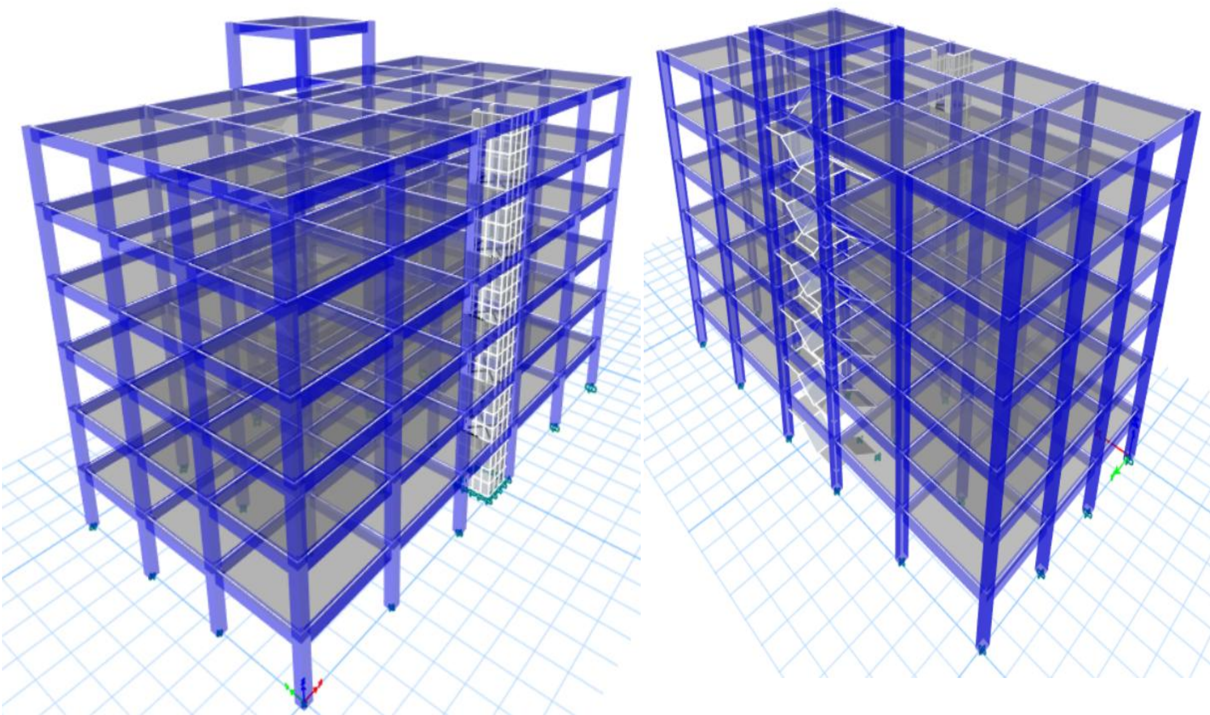


**Figure 2**: Different sides Extrude view of building from ETABS.

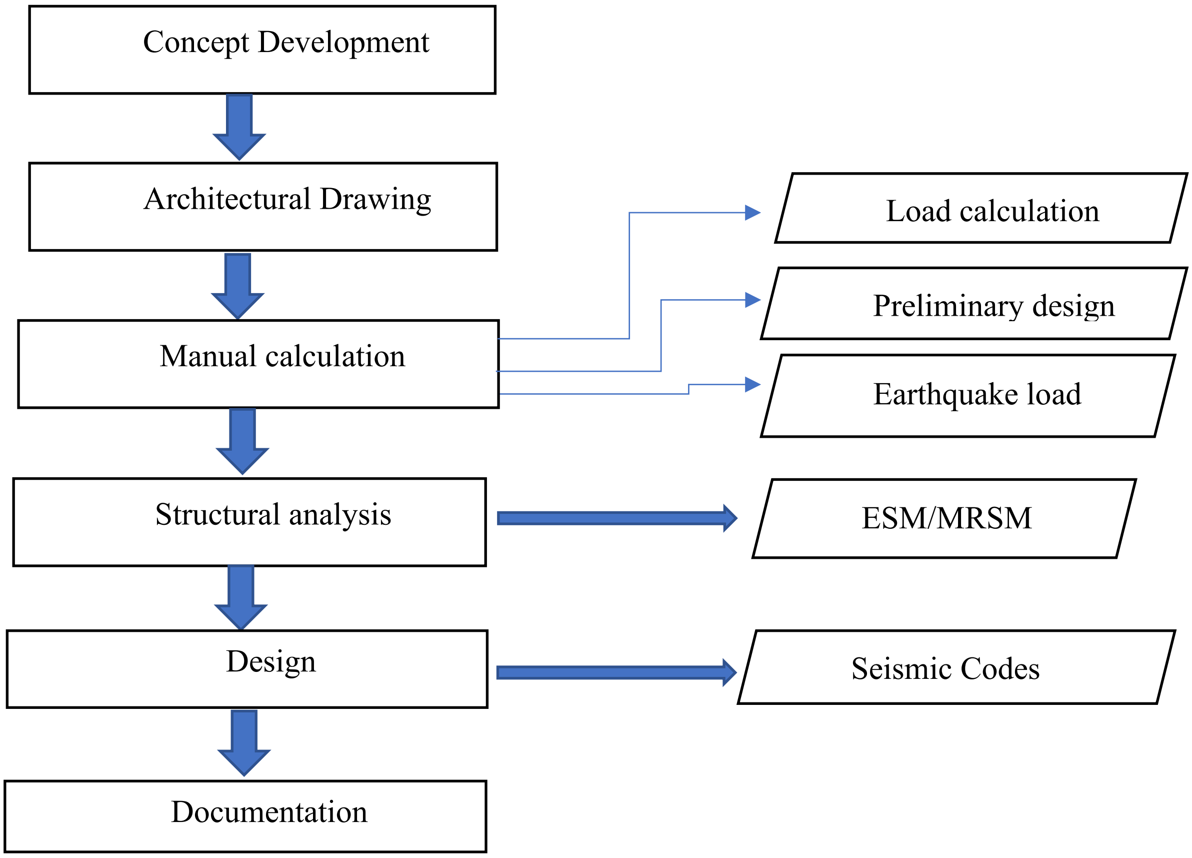



**Figure 3:** Methodology flowchart.

### 2.4 Seismic coefficient calculation:

The base shear is the total horizontal seismic force that acts at the base of a structure during an earthquake. According to IS 1893:2016 (Part 1), the base shear coefficient is determined based on various factors such as the seismic zone, importance of the structure, and the structural system's response.

The base shear is calculated using the formula:

$$V_B = Ah.W \tag{13}$$

where, $V_B$ = Total base shear (in KN)

Ah = Horizontal seismic coefficient

W= Seismic weight of the structure (in KN)

$$Ah = \frac{Z.I.Sa}{2.R.g} \tag{14}$$

Z = Zone Factor

I = Importance Factor

R = Response Reduction Factor

Sa/g = Average Response Acceleration

g = Acceleration due to gravity

From NBC 105:2020, The base shear coefficient will be determined separately for ultimate limit state and serviceability limit state from the figure 4.

Cd(T1) = (C(T1))/((Rμ)(Ωu)) (15)

Cd(T1) = (Cs(T1))/Ωs (16)

Where, Cd(T1) = Elastic Site Spectra for Ultimate Limit State

Cs (T1)) = Elastic Site Spectra for Serviceability Limit State

Rμ= Ductility Factor

Ωu = Over strength Factor for Ultimate Limit State

Ωs = Over strength Factor for Serviceability Limit State

The horizontal seismic base shear at the base of the structure in the direction is calculated as:

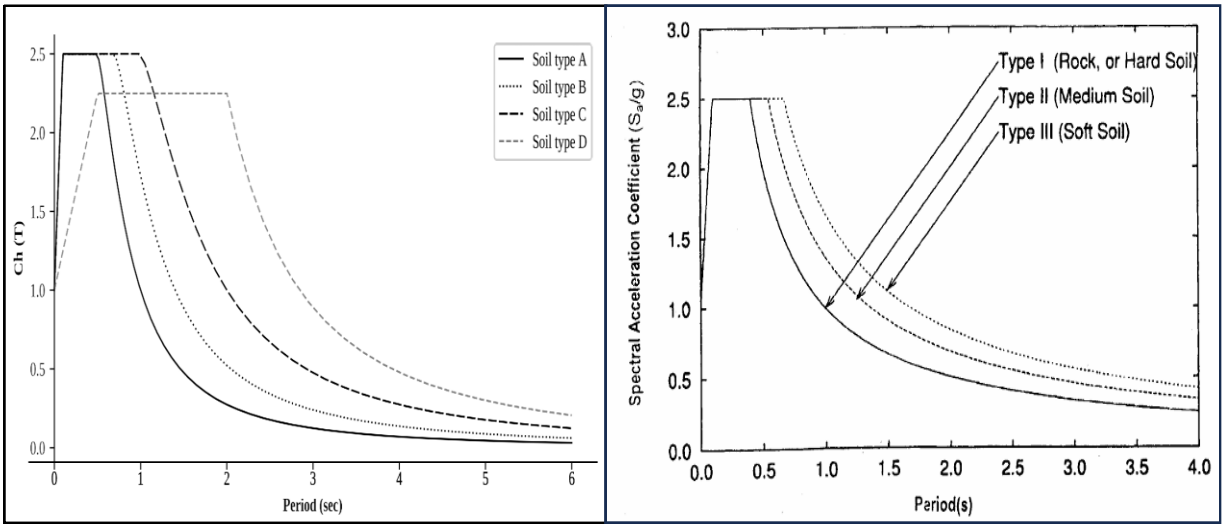
V =Cd(T1).W (17)

Where, Cd(T1) = Horizontal base shear coefficient

The Elastic site spectra for horizontal loading shall be as given by

C (T) =Ch(T) Z I (18)

where, Ch(T) = Spectral Shape factor




(a) (b)

**Figure 4:** (a) Spectral Shape Factor, Ch(T) for Modal Response Spectrum Method (NBC 105:2020), (b) Response Spectra for MRSM (IS 1893:2016)

The Vertical Distribution of Seismic Forces induced at each level 'i' shall be calculated as:

$$F_i = \frac{W_i h_i^k}{\sum_i^n W_i h_i^k} \times V$$

where Wi = seismic weight of the structure assigned to level 'i';

hi= height (m) from the base to level 'i';

n= total number of floors/levels

V= horizontal seismic base shear calculated as per 6.2

k= an exponent related to the structural period

The horizontal design spectrum for the modal response spectrum method is also different for ultimate limit state and for serviceability limit state. A separate section on structural irregularity has been added. This code includes checking the inter-story drift for both ultimate limit state and serviceability limit state as 0.025 and 0.006. Response spectrum method is performed as the combination of modal effects (such as story shear, moment, drift, displacements (Gwaccha, *et al.,* 2015; Banjara *et al.,* 2015).

**Table 3:** According to IS 875 (Part 1): 1987, Indian Standard Code of Practice for Design Loads.

| Parameters | Dead Load | Units |
|---|---|---|
| Full Brick thick External wall Without Opening | 13.46 | KN/m |
| Full Brick thick External wall 25% Opening | 10.10 | KN/m |
| Half brick thick External wall Without Opening | 8.95 | KN/m |
| Half brick thick External wall With Opening | 6.72 | KN/m |
| Full brick, 1.2 m high parapet wall | 6.18 | KN/m |
| Dead load of Floor finish for Roof | 0.75 | KN/m$^2$ |
| Dead load of Floor finish with Granite | 1.55 | KN/m$^2$ |
| Dead load of Floor finish with Tile | 1.35 | KN/m$^2$ |

**Table 4:** As per IS 875 (Part 2): 1987, Indian Standard Code of Practice for Design Loads.

| Parameters | Dead Load | Units |
|---|---|---|
| Balcony, staircase, lobby | 4 | KN/m$^2$ |
| Kitchen, conference hall | 3 | KN/m$^2$ |
| Office room with separate storage | 2.5 | KN/m$^2$ |
| Toilet, bathroom | 2 | KN/m$^2$ |
| Roof accessible | 1.5 | KN/m$^2$ |
| Roof not accessible | 0.75 | KN/m$^2$ |

## 3. Results and Discussion

A study is performed in apartment RC Building through different edition of National Building Code (NBC) from Nepal, and Indian Standard Code (IS) from India i.e. previously existing and revised standards with consideration of several design compliances. NBC 105:1994 was revised to NBC 105:2020 and also IS 1893:2002 to IS 1893:2016 which are used in current analysis. The Results are interpreted in terms of base shear, displacement, torsion, drift, lateral forces.

The seismic weight of the building under investigation is 34353.03 KN, 36281.08 KN, 36281.08 KN 34353.03 KN and 34353.03 KN derived from NBC105:1994 and NBC105:2020 (SLS), NBC 105:2020 (ULS), IS 1893:2002, IS 1893:2016 respectively. The value is same for IS 1893:2016, IS 1893:2002 and NBC 105:1994 because there is the provision to take the live load reduction factor of 0.25 (for LL<3KN/m$^2$) and 0.5 (for LL>3KN/m$^2$). Also, the value is identical for NBC 105:2000 (ULS) and NBC 105:2000 (SLS) because LL reduction factor is taken as 0.3 (for LL<3KN/m$^2$) and 0.6 (for LL>3KN/m$^2$).

Obviously, it is sure from the former case that its value shall be less than the latter case. And hence, the obtained values of seismic weight also justify the condition. Base shear identified from the analysis is shown in figure 5 along X direction and in figure 6 along Y direction. Based on the analysis, NBC 105:2020 (ULS) demonstrates higher spectral acceleration values for Type B - Medium Soil Sites compared to other investigated codes, resulting in a 45.75% increase in base shear compared to NBC 105:1994, indicating varying seismic loading criteria between revisions.

**Base Shear comparison bar chart is illustrated:**

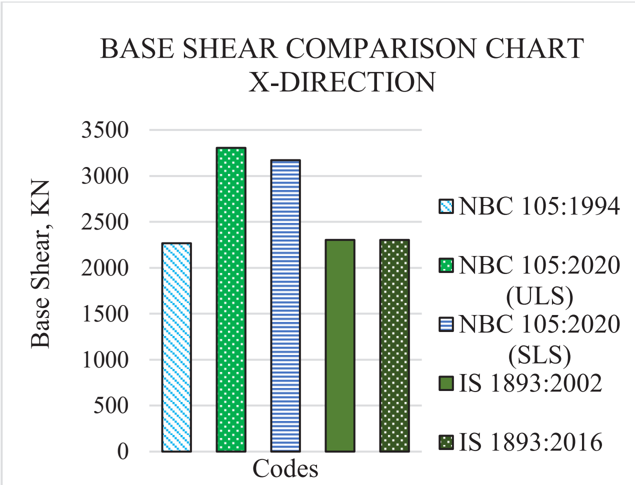



**Table 5:** Base Shear along X- Direction due to ESM/MRSM

| Codes | Value |
|---|---|
| NBC 105:1994 | 2261 KN |
| NBC105:2020 (ULS) | 3298 KN |
| NBC105:2020 (SLS) | 3171 KN |
| IS 1893:2002 | 2297 KN |
| IS 1893:2016 | 2303 KN |

**Figure 5**: Base Shear in EQX Direction from ESM/RSM.

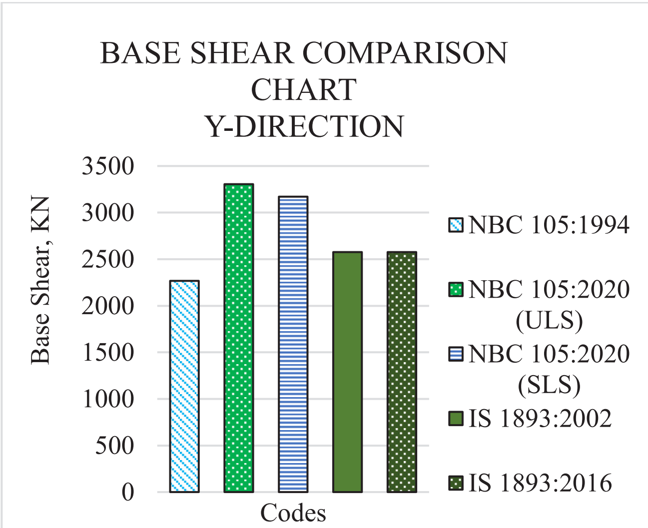



**Table 6:** Base Shear along Y- Direction due to ESM/MRSM

| Codes | Value |
|---|---|
| NBC 105:1994 | 2267 KN |
| NBC 105:2020 (ULS) | 3305 KN |
| NBC 105:2020 (SLS) | 3185 KN |
| IS 1893:2002 | 2568 KN |
| IS 1893:2016 | 2576 KN |

**Figure 6**: Base Shear in EQY Direction from ESM/RSM.

The Base shear in revised codes is increased by 45.75% of NBC codes and remains almost equal in IS codes. As compared to IS codes, NBC 105:2020 codes give more Base shear by 43.48%, considering the ULS method and by 37.66%, considering the SLS method for the same building used in the analysis.

**The story Drift ratio is presented in the line graph:**
The inter-story drift should be within the limit of different codes, as in Table 7.

**Table 7:** Comparing Elastic drift limits from different codes

| Codes | Inter story drift limit | Clause no. |
|---|---|---|
| NBC 105:2020 (ULS) | 0.024 = 2.4% | 5.6.3 |
| NBC 105:2020 (SLS) | 0.006 = 0.6% | 5.6.3 |
| NBC 105:1994 | 0.010 = 1% | 9.3, 12.6.2 |
| IS 1893:2016 | 0.004 = 0.4% | 7.11.1.1 |
| IS 1893:2002 | 0.004 = 0.4% | 7.11.1 |

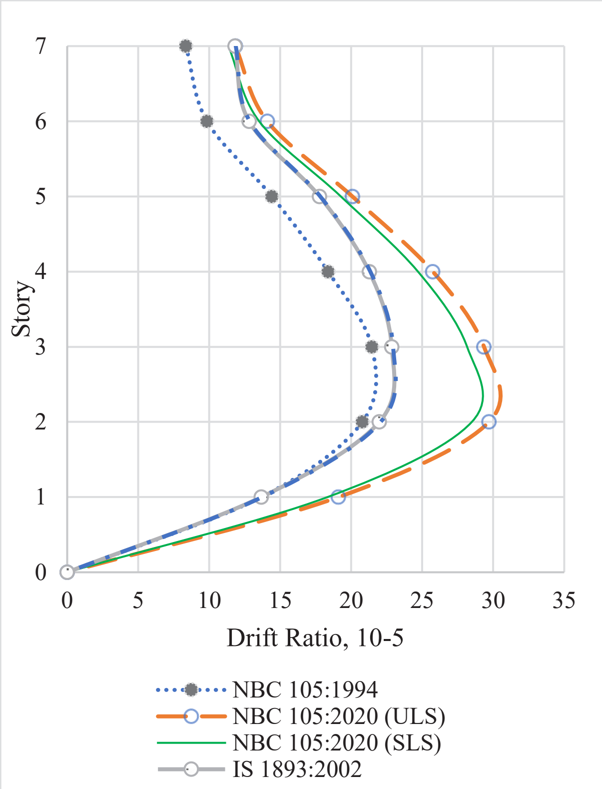



**Figure 7:** Inter Story Drift in X- Direction from ESM

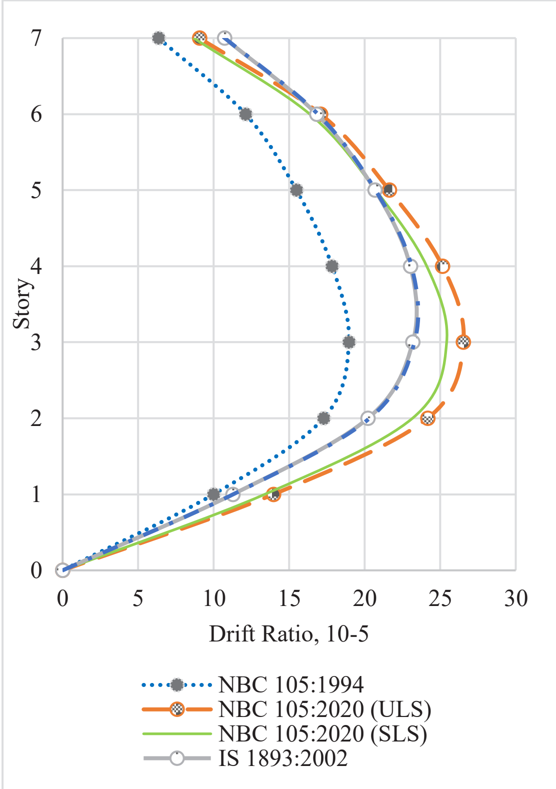



**Figure 8:** Inter Story Drift in Y- Direction from ESM

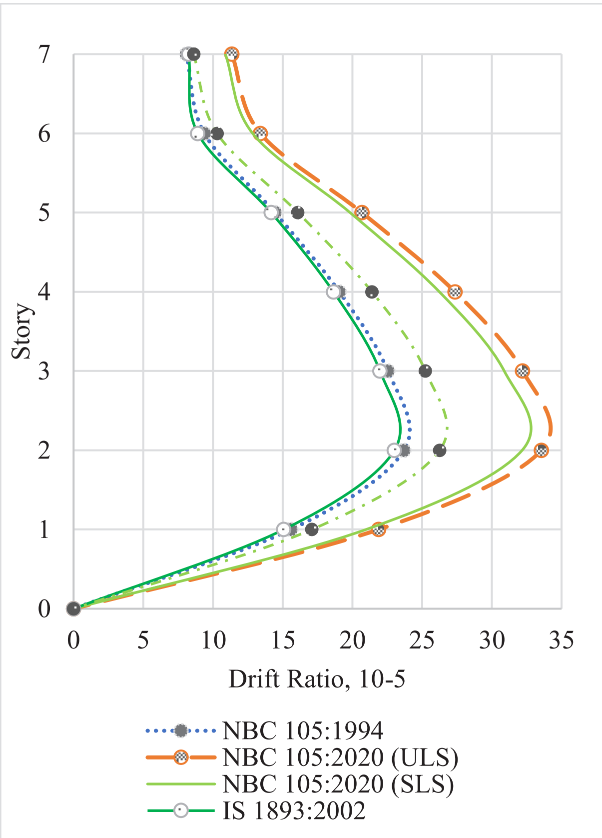



**Figure 9:** Inter Story Drift in X- Direction from MRSM

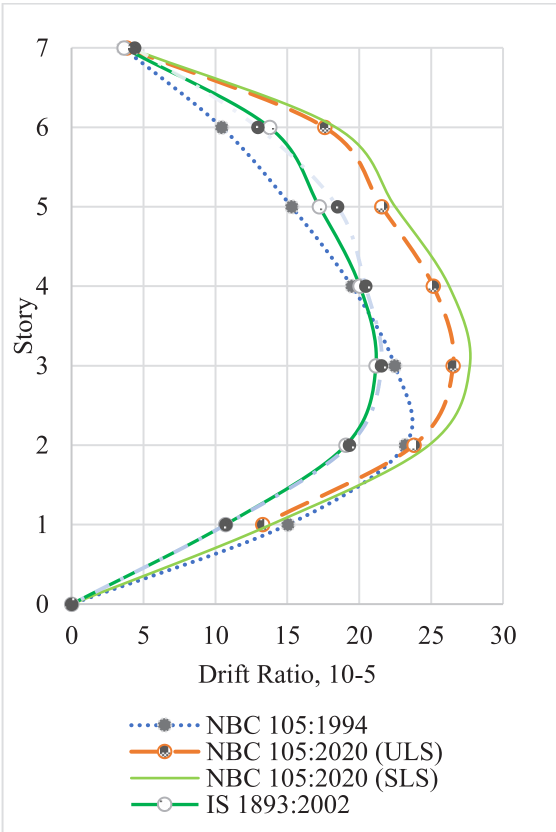



**Figure 10:** Inter Story Drift in Y- Direction from MRSM

The allowable value of the drift ratio is shown in table 2. The ISD ratio value calculated by analyzing this model is found within the value described in table 2. Figures 7,8,9 and 10 show the ISD ratio in the X and Y-direction using the ESM and MRSM, respectively.

The ISD ratio calculated by using NBC 105:2020 (ULS) gives the largest value. However, in Y-direction using MRSM, NBC 105:2020 (SLS) gives the maximum value. Both the IS codes give almost the exact value of the ISD ratio. NBC 105:1994 give the smallest value of the ISD ratio using ESM in both X and Y directions. However, using the MRSM, IS 1893:2002 gave the smallest value.

Displacement is demonstrated in line graph:

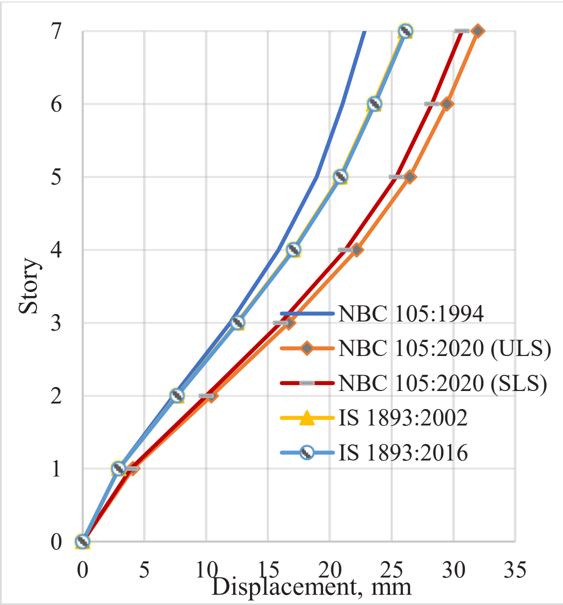



**Figure 11:** Displacement in X-Direction from ESM

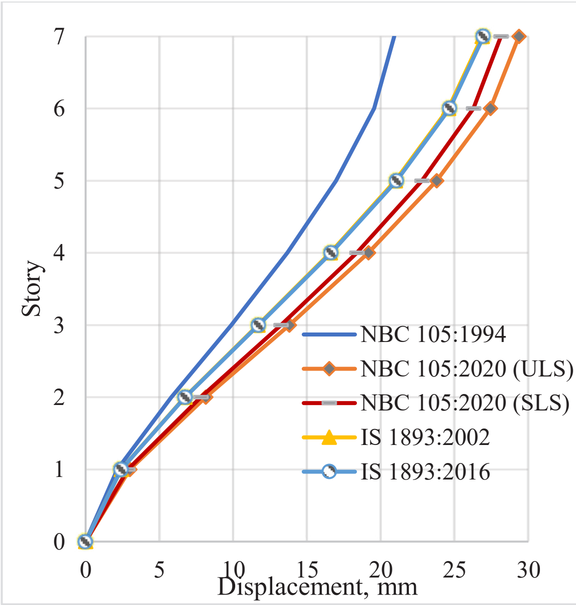



**Figure 12:** Displacement in Y-Direction from ESM

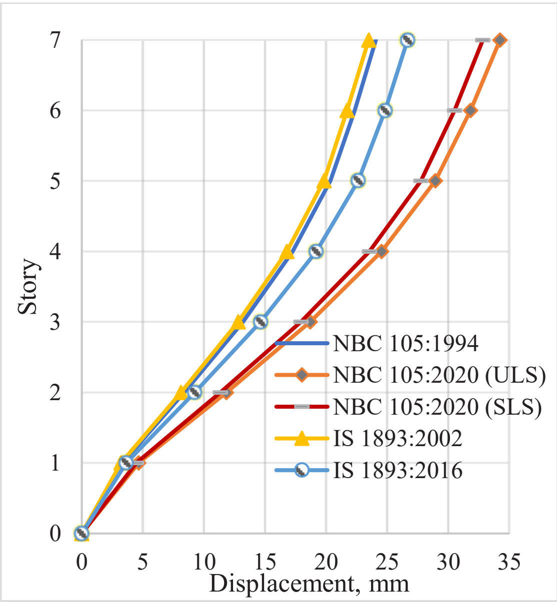



**Figure 13:** Displacement in X-Direction from MRSM

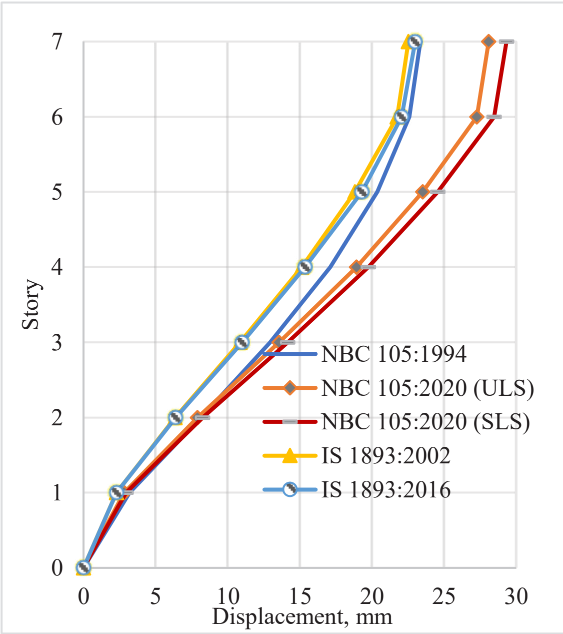



**Figure 14:** Displacement in X-Direction from MRSM

The story displacement, depicted in Figures 11,12,13 and 14 indicates that the displacement using both the IS code aligns more closely with each other. In contrast, NBC105:1994 gives less displacement than the SLS and ULS analysis using NBC105:2020. In the equivalent static method along X-direction, story design displacements from NBC 105:2020 ULS found to be 31.98mm, which is the maximum value followed by NBC 105:2020 SLS (30.685mm), IS 1893:2016 (26.164mm), IS 1893:2002 (26.065mm) and NBC 105:1994 (22.806mm) respectively.
In the Y direction also, the maximum displacement on the 7th floor is more in 105:2020 ULS (29.357mm). secondly, it is from 105:2020 SLS with 28.136mm then IS 1893:2016 gives a displacement of 26.958mm, which is slightly more than IS 1893:2002, i.e. 26.958mm. Also, we know NBC105:1994 gives less displacement of the Top floor with 20.91mm.
The deflection from MRSM was found to be more than ESM. In X direction, the displacement from NBC 105:1994 is 5.5% more in MRSM; from NBC 105:2020, the deflection at the top floor is almost 7% more in MRSM through both ULS and SLS. While it is almost the same in Indian Codes.

**The distribution of Lateral forces is given in the line graph:**

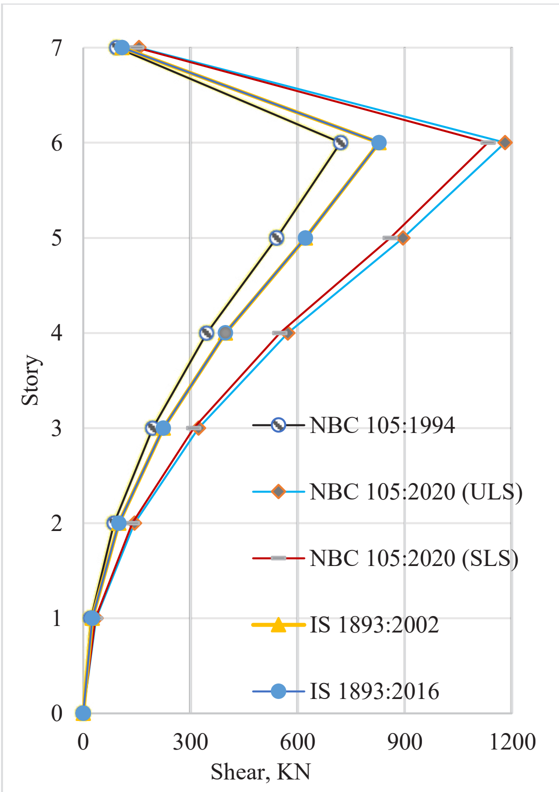



**Figure 15:** Lateral force distribution in X-Direction from ESM/MRSM

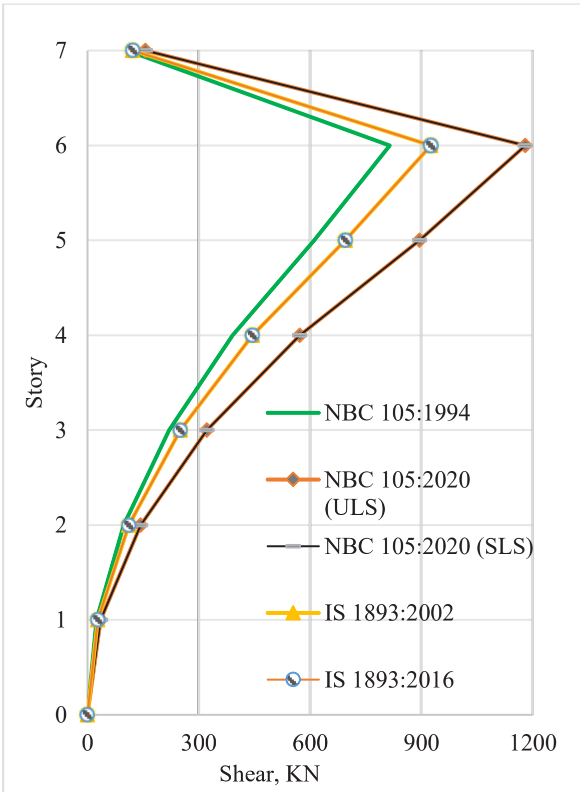



**Figure 16:** Lateral force distribution in Y-Direction from ESM/MRSM

Lateral force at each floor is distributed proportionally to the seismic weight and height of each floor. While the fundamental approach to distributing lateral forces along the height and in plan is similar in both codes, however, differences in seismic coefficients and zone factors in NBC 105 often result in higher forces for Nepal.
The lateral force in X-direction for IS 1893:2002 and IS 1893:2016 is only 2% more than NBC 105:1994 through ESM and MRSM, while for NBC 105:2020 ULS, it is 44.96% greater, followed by NBC 105:2020 SLS with a result of 39.06% more.

Also, if we measure lateral force in the Y-direction for IS 1893:2002 and IS 1893:2016, the result is 14.15% more than NBC 105:1994 through ESM and MRSM, while for NBC 105:2020 ULS and SLS, it is 44.96% greater.

**Torsion is compared in the Bar graph:**

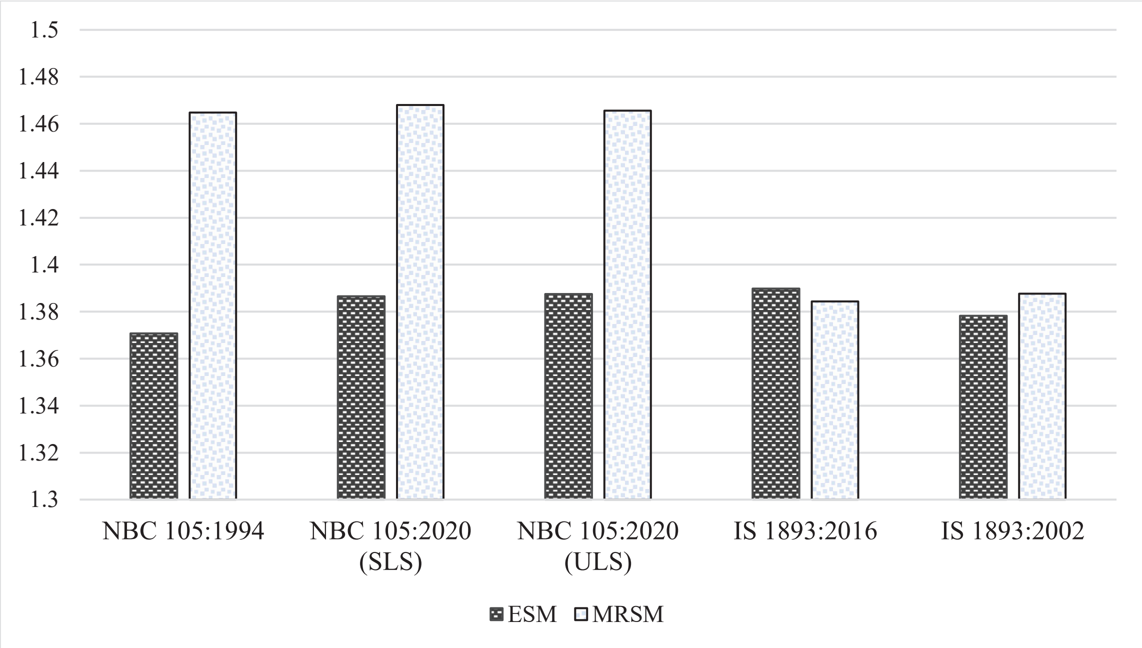



**Figure 17:** Maximum torsion in EQX Direction from ESM/MRSM

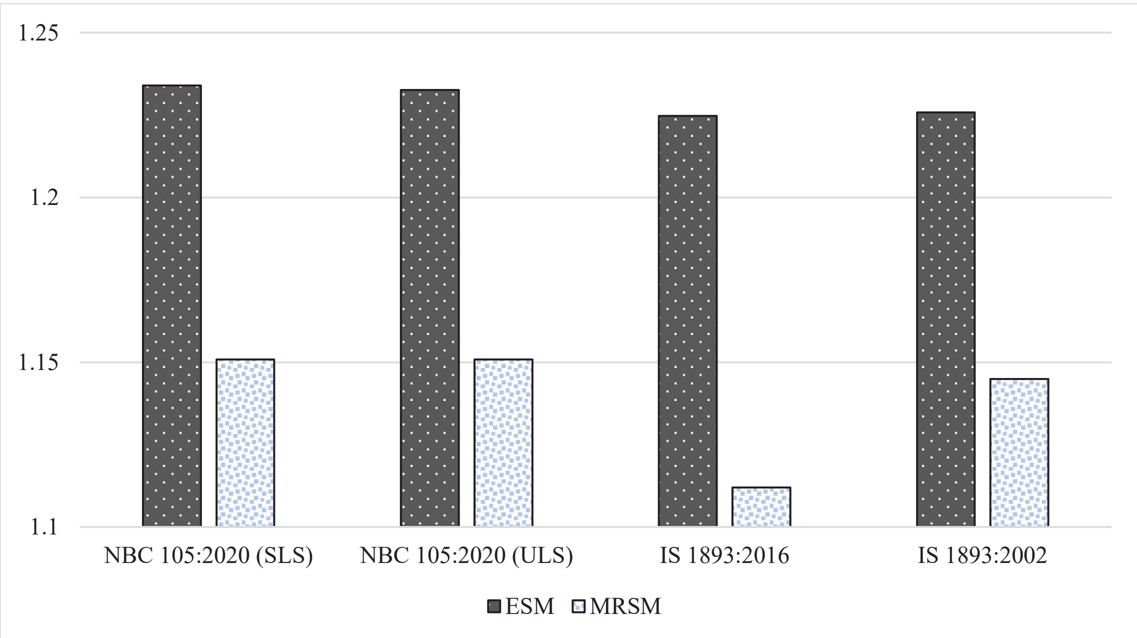



**Figure 18:** Minimum torsion in EQY Direction from RSM/MRSM.

Both countries have their own seismic design codes influenced by their respective seismic risks and geotechnical conditions. Nepalese code considers higher accidental eccentricity (10%) compared to Indian code (5%), which can result in higher torsional forces in NBC 105 designs. Buildings designed using NBC 105 typically experience higher torsional moments due to larger base shear values driven by higher seismic zone factors. Accidental eccentricity is also explicitly included to address irregularities in mass distribution.

**Beam-Column Percentage**

The percentage of average reinforcement is compared in Beam and Columns for similar conditions from different seismic codes. The average of all columns and beams is calculated through an Excel sheet and mentioned in table 8.

**Table 8:** Beam and column average longitudinal reinforcement calculations.

| Codes | NBC 105:1994 | | NBC 105:2020 | | IS 1893:2002 | | IS 1893:2016 | |
|---|---|---|---|---|---|---|---|---|
| | **ESM** | **MRSM** | **ESM** | **MRSM** | **ESM** | **MRSM** | **ESM** | **MRSM** |
| Beam % | 0.32 | 0.3 | 0.35 | 0.3 | 0.27 | 0.27 | 0.273 | 0.276 |
| Column% | 0.32 | 0.3 | 0.35 | 0.3 | 0.27 | 0.27 | 0.273 | 0.276 |
| Allowable | Max | Min | Max | Min | Max | Min | Max | Min |
| Beam % | 2.5 | 0.215 | 2.5 | 0.215 | 2.5 | 0.215 | 2.5 | 0.215 |
| Column % | 6 | 0.8 | 4 | 1 | 6 | 0.8 | 6 | 0.8 |

After completion of the structural analysis, the design of the building is carried out in accordance with the design code recommended by the relevant codes. The NBC and IS codes suggest the use of IS 456:2000, Table 4 presents the average longitudinal reinforcement percentage results for columns and beams. The NBC 105:2020 codes result in a higher reinforcement percentage, averaging around 1.28%. The IS 1893:2016 code results in an average reinforcement of 1.18%, which is the second highest.

## 4. Conclusions

- The analysis indicates that NBC 105:2020 (ULS) results in a 45.75% increase in base shear compared to NBC 105:1994, highlighting the differences in seismic loading criteria between the revisions.
- When compared to IS codes, the NBC 105:2020 codes show an increase in base shear by 43.48% under the ULS method and by 37.66% under the SLS method for the same building used in the analysis.
- The deflection found using the Modified Response Spectrum Method (MRSM) was greater than that obtained with the Equivalent Static Method (ESM). In the X direction, the displacement from NBC 105:1994 is 5.5% greater in the MRSM, while NBC 105:2020 shows a top-floor deflection that is almost 7% higher in the MRSM under both ULS and SLS conditions.
- The lateral force in the X direction for IS 1893:2002 and IS 1893:2016 is only 2% greater than that of NBC 105:1994 when using ESM and MRSM. However, for NBC 105:2020 under the ULS method, the lateral force is 44.96% higher, followed by a 39.06% increase under the SLS method.
- Overall, NBC 105:2020, along with IS 1893:2016, generally requires a higher percentage of longitudinal rebar than IS1893:2002, while NBC 105:1994 indicates the lowest requirement.
- The ISD ratio calculated using NBC 105:2020 (ULS) yields the largest value. However, in the Y-direction, the MRSM method shows that NBC 105:2020 (SLS) provides the maximum value. Both IS codes produce almost identical values for the ISD ratio.

- The Nepalese code accounts for a higher accidental eccentricity of 10%, compared to 5% in the Indian code. This difference can lead to increased torsional forces in the designs of NBC 105.
- Beam-column joints frequently do not meet the required B/C ratio criteria, necessitating adjustments to the section, size, or reinforcement.

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# Evaluating the Impact of Mason Training on Residential Building Construction: A Case Study of Pokhara Metropolitan City, Nepal

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## Abstract

This paper aims to explore the application of masonry training and its impact on the building construction sector of Pokhara Metropolitan City. The main objectives of this study are to assess current status of masons, their preference of mason training program, and its impact on the local construction industries. A sample of 368 residential buildings with plinth tie beam construction completed or in progress was selected from the study area. In total, 284 masons who have participated in the program connected to mason training were identified while visiting 368 construction sites of residential buildings. The study found that most of the masons were migrated workers in the Pokhara valley and majority of them are between the ages of 30 to 41 years. The seven-day training module emerged as the most preferred among various options, including 15-day, 30-day, and longer-duration programs. The result showed that mason training is found effective in terms of knowledge and skills. However, it has been observed that the work on the site has not been found satisfactory because of the pressure from the supervisor and contractor to speed up the works and to minimize the cost.

***Keywords:*** *Mason Training, Building, Construction Industries, Pokhara Metropolitan City*

## 1. Introduction

The theory-based research and training approaches with an empirical foundation were inspired by Campbell's (1971) analysis of the state of the training literature. Since Campbell's study, training research has expanded, produced empirically based concepts, and significantly influenced practice; as a result, the field of training research is now strong, fascinating, dynamic, active, and pertinent to companies. This paper’s aim is to give a thorough, in-depth practical study of the science behind organizational training and development. Rather than using data from education research, we predominantly rely on the training literature.

According to Hunt and Baruch (2003), some firms spend a lot of time and resources developing extensive training programs to enhance the so-called "soft skills" of management. However, it has been uncommon to evaluate the success of such projects. A method for pre- and post-training assessment has been made available by recent advancements in the utilization of survey responses. A renowned business school conducted research to evaluate the effect of interpersonal skills training on senior managers. Based on comments from subordinates collected prior to and six months after the training program, the training was evaluated. The outcome suggests that some but not all of the competencies and skills under consideration have experienced a substantial influence.

Aguinis and Kraiger (2009) cited multiple studies in European nations that relate corporate effectiveness metrics to training practices and policies. Studies like these demonstrate the importance of training in creating and sustaining a productive staff, which in turn maximizes the performance.

Vijayabanu and Amudha (2012) and Topno (2012) conducted an analytical study on effectiveness of a public sector organization's training program for various employee cadres. The outcome shows that, depending on their demographic characteristics, different employees responded differently to the training program. Additionally, it is implied that the organization's personnel's education and experience play a major role in selecting the training program.

Similarly, Saharan (2011) highlighted that the majority of organizations use employees’ input to improve training effectiveness and increase benefits. Companies subscribe to the notion that more intelligent and better-trained people enhance the possibilities of success in the never-ending quest for a competitive edge. The study explains the perspectives of workers with various backgrounds and experiences regarding the goals of corporate training.

### 1.1 Assessment of the Demand for Skilled Workers from Nepal

In the fiscal year 2020/21, GDP was projected to increase by 3.94 percent in the base price and 4.01 percent in the producer’s price. It has become challenging to achieve the projected economic growth due to the second wave of the Covid-19. An agreement between the Foreign Employment Board of Nepal and the Social Security Organization of Malaysia has been concluded with a view to make foreign employment safe, dignified and productive, and to link the Nepali workers in Malaysia with the social security program of the Malaysian government. The Directive on Sending Nepali Care Givers to Israel, 2021 has been implemented with an objective of making the process of sending support workers to the long-term care centers in Israel systematic and transparent. As of mid-March 2021, the number of workers left for foreign employment with labor permits has reached 4,466,973, out of which the number of males is 4,248,547 and females is 218,426. As of mid-March, of the fiscal year 2020/21, the number of workers who have gone for foreign employment with labor permits was 33,161 and those who have re-obtained labor permits was 52,289. Covid-19 has become the major reason behind the increasing number of reobtaining of work permits (MoF, 2020).

### 1.2 Strong, Sustainable, and Balanced Growth Requires a Skilled Workforce

The cornerstones of a policy framework for creating a workforce with the necessary skills are: making high-quality education widely accessible as a basis for future training; closely matching the skills supply to the needs of businesses and labor markets; assisting workers and businesses in adjusting to changes in technology and markets; and anticipating and preparing for the skills requirements of the future (ILO, 2000).

As a result, strong foundational skills and deeper ties between the worlds of school and work must be the cornerstones of any skills strategy. In turn, this calls for high-quality early education, accurate knowledge of changes in skill demand, responsive education and training systems to fundamental economic and social changes, acknowledgement of skills and competencies, and increased use of them in the workplace. The goals for economic and social policy must be closely linked for these policy endeavors to be successful (OECD, 2008).

### 1.3 Role of Mason in Construction Industry

Masons are essential to the building process in Nepal for all kinds of construction projects. Studies from many fields have also supported this. Masons have been identified as the primary actors in the production of 90% of the buildings in Nepal to date. Only 10% of building output is done by engineers and other professionals, especially in the urban areas. Despite playing a significant part in the development of buildings, masons have not been able to get enough support from the government to advance their knowledge and competence. Thus, it is intriguing to observe how the nation's resources are being employed to create these two important characters. According to the report, engineers use 90% of all resources, whereas 10% of all resources are used to produce masons. Masons need substantial training in lowering earthquake hazards in buildings due to their lack of official training, ignorance of earthquake-resistant technologies, and many other reasons (Parajuli, 2000).

### 1.4 Need for Mason Training

Masons are the key actors in the building construction in Nepal. However, they are not aware of earthquake technology and other knowledge that can reduce the earthquake risk. Hence earthquake risk reduction can be mainstreamed by giving the training to the masons. There are numerous reasons for the need of training for the masons. The role of mason is vital in every type of construction even in engineered construction as they are the real implementer. If they do not understand, they cannot perform accordingly and the quality does not improve. The engineers and professionals only work on papers and can tell verbally. Furthermore, the number of non-engineered buildings outweighs the engineered building where their role becomes the most important. Masons are the ones who recommend house owner on materials selection and construction process, house owners also listen more to mason than engineers. Mason has a greater role in building production in terms of quantity as well. Each mason constructs at least 3 to 4 houses every year. So, giving a training to mason has a multiplier effect (Parajuli, 2000).

### 1.5 Understanding and Teaching of Mason

This is a training for masons, and in order to accomplish the program's main goal successfully, it is crucial to first comprehend masons. Understanding masons requires familiarity with their regional building jargon, aptitude for reading blueprints, relationships with engineers and home owners, language use, assertiveness, and many other sociocultural facets. Knowing about these aspects enables the trainer to focus on the right areas and make any necessary adjustments to the delivery and field exercises without deviating from the training's core goal. The training group is typically diverse in terms of age range, work experience, language, educational attainment, and geographic area. In Nepal, the majority of masons are literate, therefore they are able to read and write. Few people are illiterate, nevertheless. Some people have even completed their college education. But the best approach is to prioritize illustrations and practical information supported by numerous instances rather than theory (Tandingan and Dixit, 2012).

### 1.6 Preparing Mason to Convince House Owners

As 90% of buildings in Nepal are currently produced under the supervision and with the participation of a head mason or a petty contractor as key actors, masons play a significant role in the construction of buildings in Nepal. Masons are the ones who advise home owners on the choice of materials and the construction process. Every year, each mason builds at least 3/4 dwellings. The owners of the homes and the masons have a close relationship. Because masons are the primary players in the construction of buildings, they can also be the important players in persuading the homeowner to support safer construction techniques and so lower the seismic risk. Therefore, one of the techniques has been to get the mason ready for persuading the homeowners (Parajuli, 2000).

Numerous studies have shown that adding specific components and improving particular construction methods can significantly lower the building's seismic risk. People believe that it costs a lot of money to make buildings earthquake-resistant. Convincing people to use safer construction practices is a difficult task for experts. Mason finds it harder to get people to recognize the value of earthquake-resistant construction. It costs more to create a structure with earthquake-resistant components, and people are obviously quite concerned about this. It clearly raises the expense of the construction, but not by as much as may be expected. Thus, it is important to clarify this impression. Mason needs to be ready for this situation (Saharan, 2011).

**1.7 Building Code Enforcement in Nepal**

Although improving the seismic performance of new building construction was the ultimate goal, the initial focus was on better understanding earthquake hazards, risks, and vulnerabilities as well as jointly developing and putting potential techniques for reducing earthquake risk into action. A persistent fatalistic worldview, a lack of catastrophe awareness, and poor policy and law all contributed to the slow implementation of National Society for Earthquake Technology (NSET). NSET has been able to advance to the point where it can currently carry out earthquake risk operations and offer technical support to other institutions in Nepal because it has a clear mission, vision, and set of strategic goals. Over time, NSET received requests from various countries to share its expertise and experiences, including those following the earthquakes in Pakistan and Gujarat as well as the 2004 tsunami in Banda Aceh (Shiwaku, 2007).

NBC-205 (1994), under Mandatory Rules of Thumb Reinforced Concrete Buildings without Masonry Infill stated that primary goal of these Mandatory Rules of Thumb (MRT) is to provide the ready-to-use dimensions and details for a variety of structural and non-structural elements for up to three-story reinforced concrete (RC), framed, typical residential buildings that are typically constructed by owner-builders in Nepal. To meet the minimal seismic safety requirements outlined by NBC 105, they want to replace the non-engineered building now used with pre-engineered construction (a draft Nepal Seismic Design Standard). This MRT is primarily meant to meet the needs of mid-level technicians (overseers and draft persons) who are not qualified to handle the structural design of buildings on their own. However, by utilizing the design processes described here, civil engineers might also use this text to make efficient use of their time.

NBC-105 (2020): Seismic Design of Buildings in Nepal is the title of this document. The document is the result of the 1994 Seismic Design of Buildings in Nepal chapter of NBC 105 being revised. This code contains the specifications for seismic analysis and design of different building structures to be built on the Federal Republic of Nepal's territory. All buildings, from low-rise to high-rise, must abide by this regulation. Buildings made of reinforced concrete, structural steel, steel concrete composite, wood, and masonry must comply with the standards of this standard. Buildings that are base-isolated as well as those that are fitted with and treated for structural control can be built with reference to specialized literature.

## 2. Materials and Methods

A mixed method has been adopted for this research. Primary data were collected in the form of questionnaire and through field observations. Whereas, secondary data were gathered from Pokhara Metropolitan City Office and peer reviewed scientific journals and articles. The study area of this research is the residential building construction projects of Pokhara valley built under the guidelines of Pokhara Metropolitan City. The building projects registered on the Pokhara Metropolitan City, under construction phase were taken for the research. As per Electronic Building System (e-bps), in fiscal year 2077/2078 & 2078/2079, 4169 and 4478 houses were registered.

The research was done by direct observation of the site, when all the mason present on the site. The total sample size of 367.8 i.e. 368 was obtained using the equation (1) given by Krejcie and Morgan (1970).

$$n = \frac{X^2\ (1-\text{p})}{e^2(N-1)+X^2p(1-p)} \qquad (1)$$

Where, n= sample size, N= population size (8647), e= acceptable error of sample size (5%), $X^2$= 3.841and p= population proportion (0.5)

For the purpose of this study, judgmental sampling was used. Houses which plinth tie beam under completed were only taken. The questionnaires were distributed proportionately among the sites and direct site observations were done.

### 2.1 Study Area

The study was carried out in Pokhara Metropolitan City. It lies in the Kaski District of Gandaki Province Nepal.

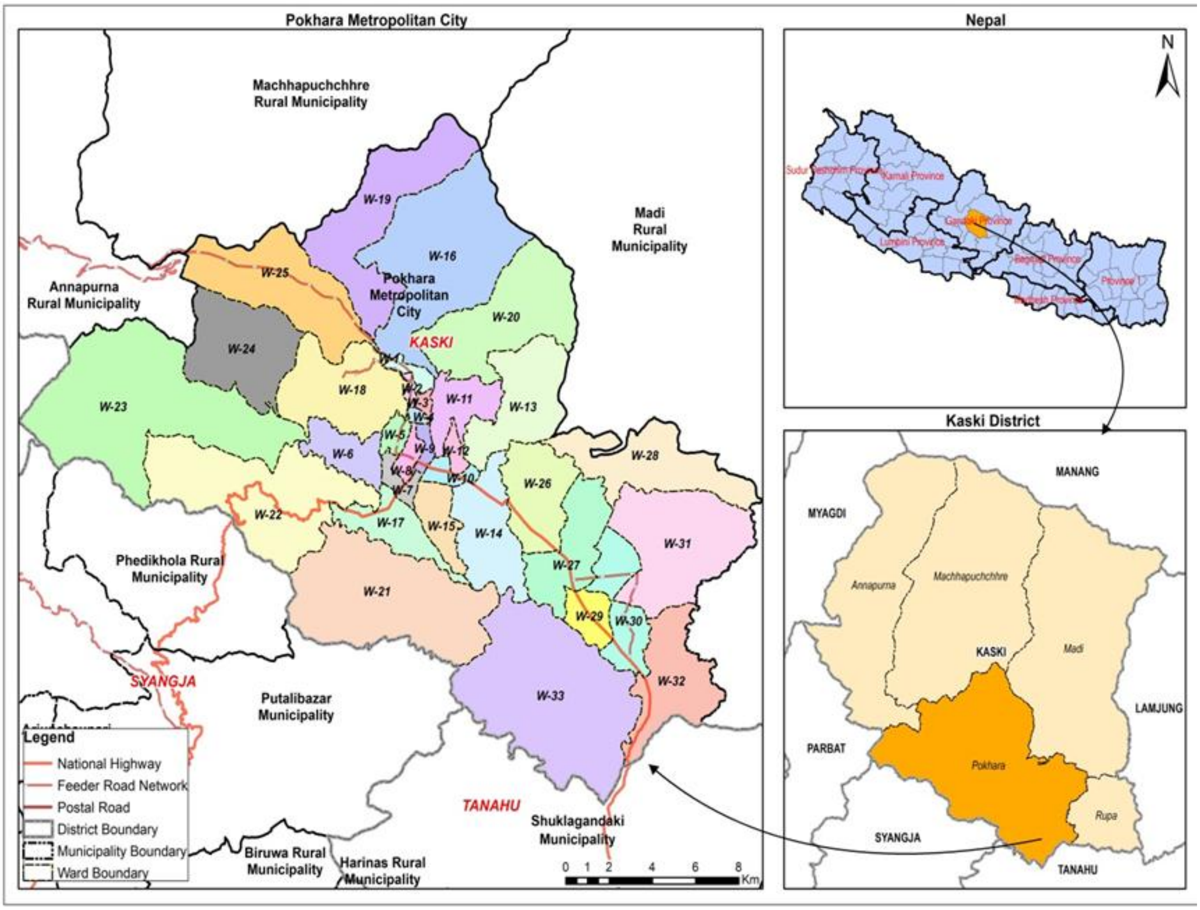


**Figure 1:** Pokhara Metropolitan City with Wards

After Kathmandu, the capital city, Pokhara is the second-largest city in terms of population. Madi Rural Municipality, Rupa Rural Municipality, Parbat and Syanja District on the East, Annapurna Rural Municipality, Syangja and Tanahu on the West, Machhapurchhre and Madi Rural Municipality on the North, and Madi Rural Municipality and Rupa Rural Municipality on the South surround Pokhara Metropolitan City. The metropolitan has categorized 17 wards in urban wards such as 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 15, 17, 27, 29 and 30 whereas 8 wards in semi urban wards such as 11, 13, 16, 18, 19, 25, 26, 32 and remaining 8 wards in rural wards. They are wards 20, 21, 23, 24, 28, 31 and 33.

## 3. Results and Discussion

The demographic characteristics of mason participated in the training program have been categorized as gender, age, education level, marital status, place of origin, category of mason, area of involvement, category of building involved and module of training. The information collected through the questionnaire regarding the demographic variables was recorded and analyzed in percentiles

**Table 1**: Demographic Profile of Respondents

| Profile | Group | Frequency | Percent (%) |
|---|---|---|---|
| **Gender** | Male | 261 | 91.90 |
| | Female | 23 | 8.10 |
| **Age** | Below 18 | 4 | 1.41 |
| | (18-29) years | 72 | 25.35 |
| | (30-41) years | 94 | 33.10 |
| | (42-53) years | 78 | 27.46 |
| | 54 and Above years | 36 | 12.68 |
| **Education** | Literate | 139 | 48.94 |
| | Illiterate | 68 | 23.94 |
| | Basic Education (1-9) | 55 | 19.37 |
| | Secondary Education (9-12) | 16 | 5.63 |
| | Higher Level | 6 | 2.11 |
| **Place of Origin** | Inside of Valley | 102 | 35.92 |
| | Outside of Valley | 182 | 64.08 |
| **Marital Status** | Married | 228 | 80.28 |
| | Unmarried | 56 | 19.72 |
| **Years of Experience** | (1-3) years | 102 | 35.92 |
| | (4-6) years | 58 | 20.42 |
| | (7-9) years | 47 | 16.55 |
| | (10-13) years | 35 | 12.32 |
| | 13 and Above years | 42 | 14.79 |
| **Category of Mason** | Skilled | 198 | 69.72 |
| | Semi-Skilled | 86 | 30.28 |
| **Area of Involvement** | Private Sector | 271 | 95.42 |

| | | | |
|---|---|---|---|
| | Public Sector | 13 | 4.58 |
| **Category of Building Involved** | Residential | 251 | 88.38 |
| | Commercial | 33 | 11.62 |
| **Module of Training** | Less than 7 days | 44 | 15.49 |
| | 7 days | 217 | 76.41 |
| | 15 days | 10 | 3.52 |
| | 30 days | 4 | 1.41 |
| | More than 30 days | 9 | 3.17 |
| | **Total (N)** | **284** | **100.0** |

Table 1 shows the demographic characteristics of the respondents. The gender distribution of the respondents shows that 78.80 percent are male while the remaining percent are female. Age group involved in construction industry in which 33.10 percent are in category of 30-41 age group likewise 27.46 percentage is 42-53 age group. Likewise, 54 and above are 12.68. But 48.94 percentage are literate whereas 23.94 percent are illiterate likewise 19.37 percentage have attended basic education and few have gained secondary and higher-level education. Construction mason involved in construction industry due to some family problems in the context of Nepal; so many leave their education after being literate thinking money is greater than education. As the study was conducted in Pokhara Metropolitan City most of the respondent are from outside of the city which is 64.08 percentage. Mason from outside the valley visit Pokhara in search of opportunity. About 80.28 percent of the respondents were married and 19.72 percent of them were unmarried. Engagement in construction industry may be increase in responsibility after marriage for income. Most of workers were from age group of 1-3 years of expertise and the least number of respondents were from group 10-13 years of experience. Most of people are interested in construction industry since their good payment system with good wages which is better than other industry. In total, 284 were respondents out of which skilled mason were 198 (69.72 %) and the rest were either semi-skilled or unskilled mason. Mason mostly gets engaged in construction industry by upgrading from labor so they are not skilled. However, 95.42 percentage and 4.58 percentage were involved in public sector construction. Billing system in private is fast and reliable than public system since bill payment system is long in the case of public system. Similarly, 88.38 percentage of respondents are involved in residential buildings and 11.62 percentage of respondents are involved in commercial buildings. Residential building construction are increasing at Pokhara as it is capital city of Gandaki Province. So, masons prefer residential building work since they should stay any day off. In addition, 76.41 percentage attended 7 days of training program and 15.49 percentage attended less than 7 days training which is similar result given by Silwal and Bhatta (2017). For instance, 7 days training program is widely organized as mason training program campaign. With attending 7 days module of training, they will miss less construction days' work at site.

**Table 2:** Descriptive Analysis of Implementation of Training Program

| Statements | Min | Max | Mean | SD |
|---|---|---|---|---|
| Mason who learnt about the basic concept and construction practices of earthquake resistant building construction. | 2 | 5 | 3.68 | 0.606 |
| Mason who knew about various codes, specification and guidelines issued by the DUDBC, GON, applicable for the earthquake resistance building construction. | 1 | 5 | 3.84 | 0.645 |
| Mason who became knowledgeable about the frequent probable errors and omissions likely to be encountered during the construction practices. | 1 | 5 | 3.88 | 0.651 |
| Mason who were involved in the real case demonstration at site right from setting layout of the building till necessary sill, bands, lintels, etc . | 2 | 5 | 4.24 | 0.696 |
| Mason who become competent in the construction of earthquake resistant structures. | 2 | 5 | 3.92 | 0.707 |
| | **Overall Mean** | | **3.91** | |

Table 2. depicts the result of descriptive analysis of the scales to assess mason involve in construction of residential building in Pokhara Metropolitan City. Respondents were asked to indicate their likeliness on implementation of mason training in construction industry of the study area through five-point Likert scale ranging from 1 being extremely disagree to 5 extremely agree. From table 2., based on the mean score 3.91, it can be said that implementation

of mason training is good at questionnaire basis. All five questions have supported implementation since their mean is above 3.5. Likewise, mean score 4.24 it can say that majority mason who were involved in the real case demonstration at site right from setting layout of the building till necessary sill, bands, lintels, etc. is highly supporting implementation on mason training program.

The result obtained from the field observation of 368 building construction sites is shown in table 3.

**Table 3:** Field Observation of Building Construction Sites

| Type of Work | Description of Items | No of House Within Criteria (Frequency) | Percent (%) |
|---|---|---|---|
| **Brick Work** | Use of correct mortar mix | 290 | 78.80 |
| | Vertical Joints Avoided | 268 | 72.83 |
| **Steel Work** | Overlap of rebar maintained at 60d | 270 | 73.36 |
| | Column bar equally cut not cut different height | 301 | 81.79 |
| | Use of chair in slab casting | 20 | 5.43 |
| **Form Work** | Use of smooth surface formwork | 70 | 19.02 |
| | Column cover maintained at 40mm | 28 | 7.61 |
| | Small portion of brick, plastic, stone, paper used to fill gap of formwork | 300 | 81.52 |
| **Concreting Work** | Use of Concrete blocks | 30 | 8.15 |
| | Use of batching box | 5 | 1.36 |
| | Use of vibrator | 368 | 100 |
| **Curing Work** | Pond curing | 368 | 100 |
| | Use of jute bag for column/beam curing | 20 | 5 |

According to field observation assessment, it was found that more than 72 % have followed the rule but it is not enough. Brickwork is the work which help labor to get upgrade to mason. Therefore, the work of brick is good in houses at most. This is supported by the findings of Hussian and Xuetong (2020). About 368 houses were on process of steel work. Similarly, 270 of 368 houses followed overlap concept of 60 times diameter of bar. Likewise, 18.21 percentage column bar were cut at different height mostly which is less in practice. Chair using while casting of slabs is also below 6 percentage. Overlap of rebar are usually followed as it is not hard to do. But column bar is equally cut at same height which is unacceptable and it is seen at 81.79 houses due to negligence of contractor and mason. As making of chair is loss of manpower time so contractor direct mason to skip chair to save their wages. Below 20 % only used smooth surface. Column cover was more than 40 mm of maximum houses which is 7.61 percentage as it is due negligence of contractor and mason workmanship. In addition, small plastic, bricks, etc. were used to fill gap of formwork in construction building which is 81.52 percentage which is worst and it is because contractor is saving money for buying good formwork as old formwork as at use. Maximum constructions site did not use concrete block; batching box was not seen at any sites. Vibrator was used remarkable which is 100 percentage. Unregular stone are observed at site as it is easily available and making of concrete block takes time and client is unaware of concrete block. Ponding curing was at almost all site we visited but jute bag curing for beam and column was just observed at 20 building constructions site. Client, mason is unaware about curing system of jute bag and client also does not buy jute bag to save costing.

## 4. Conclusions

The study revealed that mason knew well about the content of mason training program which shows the positive impact of training program. Moreover, the status of training, awareness programs, and knowledge retention among masons was found to be satisfactory. While the questionnaire survey indicated effective learning, field observations revealed a gap between knowledge and practical implementation. In many cases, trained techniques and knowledge were not applied on-site. This discrepancy was attributed to pressure from supervisors and contractors to accelerate progress and reduce costs, often at the expense of quality. These results highlighted the requirement of monitoring of work, refresher training and upgrading 7 days of module of training program. It was also found that there were inadequate training programs in the study area due to lack of required trainers as compared to the construction works done by the masons. Further, the study identified that there is a growing demand for skilled masons in Pokhara to meet the workforce requirements of the rapidly growing construction sector.

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# Enhancing Compressive Strength in M45 Grade Concrete: A Comparative Evaluation of Micro-silica and Alccofine as Partial Cement Replacements

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**Abstract**

This study investigates the compressive strength and durability of M45 grade concrete using Micro-silica and Alccofine as partial replacements for cement. Experimental results indicate that Alccofine-based concrete achieves 28-day compressive strengths of up to 60.6 MPa at 10% replacement, outperforming Micro-silica-based mixes by 55.2 MPa. Alccofine also enhances workability, with slump values peaking at 144 mm and 135 mm for Micro-silica. The optimal replacement level for both materials is 10% by cement volume, where Alccofine's dual pozzolanic-cementitious reactivity improves microstructure densification, reducing permeability and enhancing durability. These findings position Alccofine as a superior additive for high-strength concrete applications, offering significant mechanical and durability advantages.

**Keywords:** Concrete, Compressive Strength, Micro silica, Alccofine, M45 Grade Concrete, Cement Replacement, Workability

## 1. Introduction

Concrete remains the backbone of modern infrastructure, with high-strength variants increasingly demanded for critical structures. Supplementary cementitious materials (SCMs) like Microsilica and Alccofine are pivotal in enhancing concrete performance by reducing cement content and improving workability and durability. While Micro-silica is well-established, Alccofine, an ultrafine, high-reactivity SCM, offers unique advantages, including reduced water demand and enhanced early-age strength (Narender Reddy et al., 2018). However, comparative studies on their efficacy in $M_{45}$-grade concrete remain limited, particularly at varying replacement levels. The concrete composition is of coarse aggregates, fine aggregates, cement, and water. Additives such as plasticizers, fly ash, Alccofine, and Microsilica are commonly used to enhance the strength and durability of high-performance concrete. In this research, standard grade concrete from the Seti River basin coarse and fine aggregate is studied, potentially including crusher plant materials from the Kaski district.

This study was carried out to identify optimal replacement levels for both SCMs and compare the compressive strength of Alccofine- and Microsilica-based M45 concrete. Existing studies focus on individual SCMs, leaving a gap in direct comparisons between Alccofine and Microsilica in high-strength mixes. This study addresses this gap by evaluating their compressive strength, workability, and microstructural interactions.

In most cases, fine and coarse aggregate adjustment is necessary to supplement the grading by adding respective size fractions, which may be deficient in the aggregate as found in the gradation analysis (M L Gambhir, 2006). The cement replacement by 10% of Alccofine gives higher values for all other mixes. Alccofine incorporated mortar cubes almost 15% to 20 % higher than the conventional cement concrete (Balamuralikrishnan and Saravanan, 2021). A study comparing the effects of various SCMs found that blends of Alccofine and Micro silica resulted in superior compressive strength and reduced permeability, indicating their effectiveness in improving concrete performance (Abrahimi and Bhikshma, 2024).

### 1.1. Alccofine-1203

Alccofine-1203 is a specially treated product based on high glass content with high reactivity obtained through controlled granulation. The raw materials are composed of low-calcium silicates—the processing with other selected ingredients results in controlled particle size distribution (PSD). The computed blain value based on PSD is around 12000 cm$^2$/gm and is ultra-fine. Due to its unique chemistry and ultrafine particle size, Alccofine-1203 provides reduced water demand for given workability, even up to 70% replacement level as per the requirement of concrete performance. Alccofine 1203 can also be used as a high-range water reducer to improve compressive strength or as a super workability aid to improve flow.

### 1.2. Micro-silica Fume

Silica Fume is generally proposed as the appropriate cement extender where high strength, low permeability are the prime requirements. Though silica fume is known to improve durability, its addition in concrete is often negated by the increase water and/or admixture dosage required to improve the workability and handling properties of the fresh concrete.

Alccofine is a new pozzolanic material bringing a technical revolution to the construction industry. The survey found that the alccofine can achieve high strength when it is replaced by cement at 0%-20 % compared to the traditional concrete (Reddy and Thiruvadi, 2017). Results have shown that adding Al and nano-silica (Ns) to concrete decreased weight and compressive strength. The increase in temperature above 600ºC affected the compressive strength of the Al + Ns mixes more than the control mixes. At 1000ºC, excessive micro-cracking is also observed. Increased fire duration substantially increased concrete degradation (Ashwini and Srinivasa Rao, 2021). The present study is the influence of Alccofine on cement mortar cubes by replacing the cement by Alccofine with various proportions like 5%, 10%, 15%, 20% were cast and tested in the laboratory as per Indian Standard 4301-1988 (Part-6) and the results were analysed and presented in the form of charts and graphs. It is observed that the early age strength is obtained for all the combinations, but 10 per cent of Alccofine yields more strength than other dosages (Balamuralikrishnan and Saravanan, 2021). These materials are easy to mix and can be mixed directly with cement; ultrafine particles provide a better and smoother surface finish. The results of these materials were found to significantly increase their strength (Reddy, Mounika and Moulika, 2018).As the temperature rises above 600ºC, control mixes performed better than the concrete mixes using nanosilica and alccofine (Ashwini and Srinivasa Rao, 2021).

## 2. Materials and Methods

The methodology involved conducting laboratory tests according to the IS code standards. The data were analysed and compared with the standard provisions outlined in the IS codes. Both primary and secondary test results were analysed qualitatively and quantitatively, compared with standard IS code provisions.

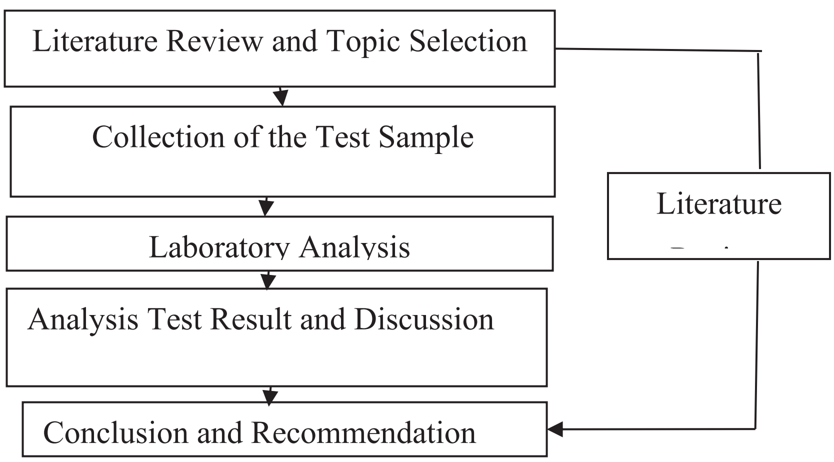


**Figure 1:** Research Frameworks

Research was carried out within the Pokhara Metropolitan City of the Seti River basin, on crushed aggregate; most of the concrete material in the Seti basin was produced for ethical research and the secrecy of crusher plant material test results obtained from the laboratory testing. The researcher team only identifies which crusher plant has the test results.

Experimental data were studied and related to Indian Standard Code provisions, and test procedures were carried out using IS 383:2016 (Bureau of Indian Standards, 1970). Three samples were collected from the crusher plant by slicing, and sample screening was done to test the physical and mechanical properties of the crusher plant, whose material is used for constructing infrastructure within the Kaski district of Nepal. The average value obtained from the three samples was calculated and compared with the standard value in the code IS 383:2016 (Bureau of Indian Standards, 1970). All the laboratory tests were conducted in Barahi Technical Solutions Pvt Ltd., which was certified and calibrated by the Government of Nepal, Nepal Bureau of Standards for material testing. The methodological flow chart applied in this study is shown in Figure 1.

The research was based on the IS code provision of standard concrete with grades of $M_{45}$ using Nepal Standard OPC cement and IS standard Alccofine and Silica fume. The specified laboratory test was conducted under normal laboratory temperature and pressure, and seasonal variation on the sample's properties and the geological properties of the aggregate sample was not considered. The physical and mechanical properties of coarse and fine aggregates are presented in Table 1, while the chemical properties of Alccofine and silica fume are provided in Table 2. The Los Angeles abrasion value, Aggregate Impact Value (AIV), and Aggregate Crushing Value (ACV) for the coarse aggregate were found to be 33%, 21%, and 26%, respectively.

**Table 1:** Physical and Mechanical Properties of Coarse and Fine Aggregate

| Sample Name | Gradation | Sp Gravity | Water Absorption (%) | Particles Finer than 75 microns (%) | FI and EI (%) |
|---|---|---|---|---|---|
| **Fine Aggregate** | Zone II | 2.62 | 1.78 | 2.3 | - |
| **Coarse Aggregate** | Single size 20 down | 2.69 | 1.01 | 0.6 | 15 and 17 |

Table 1 confirms that both physical properties of the research source satisfy the specification declared by the code provision.

According to IS 383:2016 (Bureau of Indian Standards, 1970), aggregates with particles smaller than 4.75 mm are classified as fine aggregates (commonly known as sand), while those with particles larger than 4.75 mm are classified as coarse aggregates. The specific gravity test is a key indicator of aggregates' density and water absorption properties. It helps identify the suitability of stones for construction purposes. Aggregates with high water absorption are generally more porous. They are often deemed unsuitable for construction unless their strength, impact resistance, and hardness are proven adequate through additional testing. Fine particles smaller than 75 microns, as determined by the IS sieve, exhibit unique characteristics. When mixed with water, these particles behave like emulsions, displaying slight plasticity or non-plasticity regardless of moisture content. When air-dried, such particles typically show little to no strength, making them less desirable for construction applications. The shape of aggregate particles, particularly the presence of flaky and elongated particles, plays a significant role in determining the quality of the aggregate. In applications such as base courses, bituminous concrete, and cement concrete, flaky and elongated particles are generally undesirable. Their presence can lead to inherent weaknesses, increasing the likelihood of structural failure under heavy loads. The mechanical properties of the coarse aggregates used in this study comply with the specifications outlined in IS 383:2016, ensuring their suitability for construction purposes.

**Table 2:** Chemical Properties of Cement, Alccofine and Micro-silica Fume (Anisur Rahman, 2017)

| Sample Name | Calcium oxide (CaO) | Silicon dioxide ($SiO_2$) | Alumina ($Al_2O_3$) | Magnesium oxide (MgO) |
|---|---|---|---|---|
| **Alccofine 1203** | 43.92 | 27.53 | 16.26 | 5.82 |
| **Silica Fume** | 0.86 | 86.25 | 1.52 | 1.32 |

The work is to design the mix portion for Alccofine 1203, partially replacing the conventional cement in various percentages such as 2%,4 %, 6%, 8%, 10%, 12%, and 14%, and the compressive strength of the partially replaced Alccofine 1203 and Micro-silica fume in standard concrete grade of $M_{45}$ as per IS 456:2000 (IS 456, 2000).

**Table 3:** Various Ingredient Uses for Concrete Preparation

| Sample Name | Fine Aggregate | Coarse Aggregate | Water | Admixture | Cement |
|---|---|---|---|---|---|
| **Concrete Grade M45** | 712 | 1097 | 161.7 | 3.43 | 485 |

The experimental investigations were planned to study concrete partially when added with cement replacement material (CRM). Different mix proportions are designed and standardised. The study aims to determine the compressive strength and workability of various mix proportions organised for testing. Six cubes of each percentage, 42 cubes for Alccofine and 42 cubes of Micro silica, were prepared for the concrete mix proportions and cured under controlled conditions until they were ready for testing. The compressive strength of the designed concrete was carried out as per the IS code at 7 and 28 days of cement, with cement replacement material by micro silica and Alccofine and compared with the target strength.

## 3. Results and Discussion

The test specimens were cast, cured, and tested, and the results are presented in this section. The M45 design mix was prepared and cast into cube specimens to achieve high-performance concrete. The primary objective of this study was to determine the compressive strength of concrete, and to this end, the properties of the constituent materials were evaluated through standard laboratory tests.

The compressive strength of the concrete cubes was measured for mixes incorporating varying percentages of silica fume and Alccofine. The results for both 7-day and 28-day compressive strengths are tabulated below, providing a comparative analysis of the performance of the different mixes. Alccofine's peak strength was at 10% replacement (60.6 MPa at 28 days), declining thereafter. Micro-silica's maximum strength was at 8% (55.2 MPa), with earlier strength gain but lower ultimate performance.

**Table 3:** Compressive Strength of 7 and 28 Days

| Sample Name | 2% | 4% | 6% | 8% | 10% | 12% | 14% |
|---|---|---|---|---|---|---|---|
| | | | **7 Days Compressive Strength** | | | | |
| **Alccofine 1203** | 40.4 | 56.4 | 55.3 | 51.1 | 47.4 | 46.2 | 44.1 |
| **Silica Fume** | 33.2 | 48.5 | 49.3 | 50.4 | 49.2 | 45.7 | 42.15 |
| | | | **28 Days Compressive Strength** | | | | |
| **Alccofine 1203** | 47.2 | 60.4 | 60.6 | 58.2 | 57.2 | 52.4 | 51.9 |
| **Silica Fume** | 41.3 | 54.3 | 54.7 | 55.2 | 54.3 | 52.1 | 51.85 |

The slump value of the concrete was measured for mixes incorporating varying percentages of silica fume and Alccofine. The results for both additives are tabulated below, Alccofine use slump increases steadily from 80 mm (2%) to 144 mm (10%), then declines at higher replacements (135 mm at 12%, 129 mm at 14%), micro silica use slump rises from 70 mm

(2%) to 135 mm (10%), then decreases to 124 mm (14%), providing a comparative analysis of the performance of the different mixes. Alccofine mixes showed superior slumps of 144 mm and 135 mm for Micro-silica at 10%, attributed to its ultrafine particles reducing inter-particle friction.

Table 4: Alccofine and Micro Silica Slump Value at Various Percentage Use

| Sample Name | 2% | 4% | 6% | 8% | 10% | 12% | 14% |
|---|---|---|---|---|---|---|---|
| | | | Slump Value (mm) | | | | |
| **Alccofine 1203** | 80 | 100 | 125 | 131 | 144 | 135 | 129 |
| **Silica Fume** | 70 | 95 | 115 | 128 | 135 | 130 | 124 |

**4. Conclusions**

The experimental findings depict that the appropriate substitution level of Alccofine and Micro-silica in M45 Grade Concrete is 10% by volume of cement. Curing ages of concrete at seven and twenty-eight days were carried out and compared results between Alccofine-based concrete and Micro silica-based concrete, at this replacement level, Alccofine-based concrete strengthened was 60.6 MPa, while Micro silica-based concrete had 55.2 MPa, which is 9.78% more.

Workability using Alcocofine at a 10% dose is 144mm, and that of Micro silica is 135mm, which shows that Alcocofine enhances the slump by 6.7% at the optimal dosage. The key aspect responsible for this benefit is Alcocofine's dual nature, which allows it to participate in pozzolanic and cementitious reactions. The dual reactivity of Alcocofine reduces pore size, improving impermeability and chemical resistance.

**Recommendations:**

- Alccofine is preferred for M45 concrete in load-bearing structures.
- Further studies on long-term durability (e.g., chloride ingress, carbonation) are warranted.

**Declaration of Competing Interest**

The authors assert that they have no known competing financial interests or personal relationships that could have appeared to compel the work reported in this paper.

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# REVIEW OF EVOLUTION OF STUDIES IN EQUIPMENT PRODUCTIVITY IN CONSTRUCTION

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## Abstract

The study of equipment productivity in construction has evolved significantly over time, driven by the industry's need to improve efficiency, reduce costs, and enhance overall project performance. Equipment productivity refers to the effectiveness with which construction machinery completes assigned tasks, typically measured in terms of output per unit of input. Early research focused on mechanical efficiency, operator proficiency, and equipment reliability, while recent studies have embraced digital monitoring, automation, and artificial intelligence (AI). The integration of Internet of Things (IoT) technology and predictive analytics has further enabled real-time tracking, proactive maintenance, and optimized resource allocation. This review studies the evolution of methodologies in equipment productivity research, from observational studies to AI-driven techniques. Key factors influencing productivity include operator skills, maintenance practices, site conditions, and technological advancements. Challenges such as data inconsistencies, cost constraints, and resistance to technology adoption remain prevalent. The emerging trends such as machine learning and sustainable practices are critical areas for future research. By synthesizing past and present studies, this review provides valuable insights for researchers, industry professionals, and policymakers, aiming to improve equipment productivity in construction through innovation and data-driven decision-making.

***Keywords:*** *construction equipment, decision making, efficiency, productivity*

## 1. Introduction

The efficiency with which an equipment completes assigned task determines its productivity. Productivity can be measured through parameters such as consumption of fuel, working hours, operational efficiency. Like any other industry, there is a need to reduce cost and enhance performance of equipment in the construction industry leading it to evolve from past few decades. As construction projects become more complex and mechanized, ensuring optimal equipment utilization has emerged as a key determinant of project success. The construction industry, which plays a crucial role in economic development worldwide, has long faced challenges related to productivity stagnation, cost overruns, and schedule delays. To address these issues, researchers have sought to identify the factors influencing equipment productivity, including operator skill levels, maintenance practices, and technological advancements. With rapid digital transformation and the integration of emerging technologies such as automation, artificial intelligence (AI), and the Internet of Things (IoT), the evolution of studies in equipment productivity offers valuable insights into past trends, current challenges, and future opportunities (Hasan et al., 2018).

Over the decades, research in construction equipment productivity has focused on multiple aspects, including material handling, excavation, and concrete work, among others. Early studies emphasized traditional factors such as mechanical efficiency, equipment reliability, and operator proficiency as primary determinants of productivity(Dixit et al., 2019). However, as the industry advanced, researchers began to explore broader influences such as automation, data analytics, and digital monitoring tools. For instance, Salem (2017) examined the impact of equipment age, payload capacity, and road conditions on hauling equipment efficiency, highlighting the significance of these variables in earthmoving operations. Similarly, (Zhu et al., 2017) introduced a vision-based framework for tracking workforce and machinery in job sites, demonstrating the potential of computer vision for real-time productivity monitoring. Other studies, such as those by Deokar and Kulkarni (2018), investigated the performance of hydraulic excavators, identifying critical factors like fuel quality, operator experience, and proper attachment usage. Additionally, systematic literature reviews, such as those conducted by Hasan et al. (2018), have synthesized decades of research to identify persistent productivity impediments, including inadequate supervision, poor scheduling, and inefficient resource allocation. The industry's increasing reliance on data-driven decision-making has also led to studies exploring the role of predictive maintenance, automation, and IoT-enabled solutions in optimizing equipment management and scheduling.

This review paper examines the evolution of research on equipment productivity in construction, tracing how studies have progressed from observational analyses to AI-driven methodologies. By synthesizing findings from multiple research contributions, this review explores key trends, methodologies, and technological advancements that have shaped the field. Early research primarily relied on manual data collection methods, such as site observations and productivity logs, to assess efficiency. However, the advent of digital technologies has facilitated the shift towards real-time tracking systems, automated data collection, and machine learning-based analytics. Recent studies have explored how AI-driven predictive models can forecast equipment failures, optimize fleet utilization, and minimize downtime through proactive maintenance strategies. Moreover, the integration of IoT in construction equipment has allowed for continuous performance monitoring, enabling project managers to make data-driven adjustments in real time(Khoury et al., 2018). Despite these advancements, challenges remain in achieving consistent productivity improvements across different construction environments. Variability in site conditions, labor expertise, and project-specific requirements necessitates tailored approaches to equipment productivity enhancement. This review highlights the key knowledge gaps in existing research and proposes potential areas for further investigation, such as the standardization of digital monitoring systems, the cost-benefit analysis of automation adoption, and the integration of AI-driven decision-making frameworks in construction equipment management.

As construction productivity remains a critical concern for industry stakeholders, understanding the evolution of research in equipment productivity is vital for developing innovative solutions to persistent challenges. The continuous progression from traditional empirical studies to technology-enhanced research underscores the industry's commitment to improving efficiency through innovation. By analyzing historical research trends, this review provides a structured narrative of how the study of equipment productivity has evolved over the years. It examines how methodologies have shifted, from early qualitative assessments to sophisticated, data-driven techniques that leverage automation, AI, and digital monitoring. The insights presented in this review will be valuable for construction professionals, researchers, and policymakers seeking to optimize equipment utilization and enhance overall project performance. As the construction industry continues to embrace digital transformation, future research should focus on integrating emerging technologies, addressing implementation barriers, and developing standardized frameworks for measuring equipment productivity. Through informed decision-making and strategic adoption of technology, the construction sector can achieve higher efficiency, lower costs, and improved sustainability in equipment management and operations.

In addition to traditional and existing practices, emerging technologies such as autonomous construction machinery, digital twin simulations, and integrated cyber-physical systems are redefining how productivity is conceptualized and improved in construction environments (Sacks et al., 2020).

## 2. Equipment productivity in construction industry

### 2.1 Key Factors Affecting Equipment Productivity in Construction

The study of equipment productivity in construction has been a focal point for researchers over the years, with various factors identified as critical to optimizing performance(Al Sinaidi and Poloju, 2022). Early studies, such as those by Salem et al., highlighted that excessive loads, poor road conditions (including muddy and snowy roads), and the age of equipment were significant factors affecting productivity. These findings were based on a questionnaire-based methodology involving 80 construction professionals, with 26 responses analyzed using fuzzy set theory. The study developed a framework that converted expert linguistic evaluations into numerical values, serving as an early warning system for contractors to make proactive decisions (Salem et al., 2017).

Further research by Deokar and Kulkarni expanded on these findings by focusing on hydraulic excavators. Through direct site observations and surveys, they identified equipment efficiency, operator skill, fuel quality, and improper attachment usage as key factors impacting productivity. The study also pointed out bad practices such as insufficient training, low-quality lubricants, and poor communication between supervisors and operators, emphasizing the need for better training programs and optimized equipment usage strategies (H and S, 2018).

In a more recent study, Poudel et al. (2023) examined road construction projects in Nepal and identified equipment condition, operator skill, availability of skilled labor, and insufficient equipment numbers as the most crucial factors affecting productivity. Using the Relative Importance Index (RII), the study ranked these challenges and proposed solutions such as mandatory operator certification, better wages, and regular training (Poudel et al., 2023). Similarly, Dara (2022) investigated material and equipment (M&E) productivity, identifying inadequate equipment selection expertise, poor maintenance, and inconsistent routine checks as key challenges. The study emphasized the importance of proper procurement, training, and operational efficiency in enhancing productivity (Dara, 2022).

Chandra et al. (2023) further categorized the factors affecting equipment productivity into six primary categories: management, materials, human factors, technical aspects, environmental conditions, and other factors as shown in Figure 1. Their study, using Structural Equation Modeling (SEM), found that materials-related factors (e.g., operating life and age of equipment) and external constraints (e.g., construction accidents) had the most significant impact on productivity (Chandra et al., 2023).

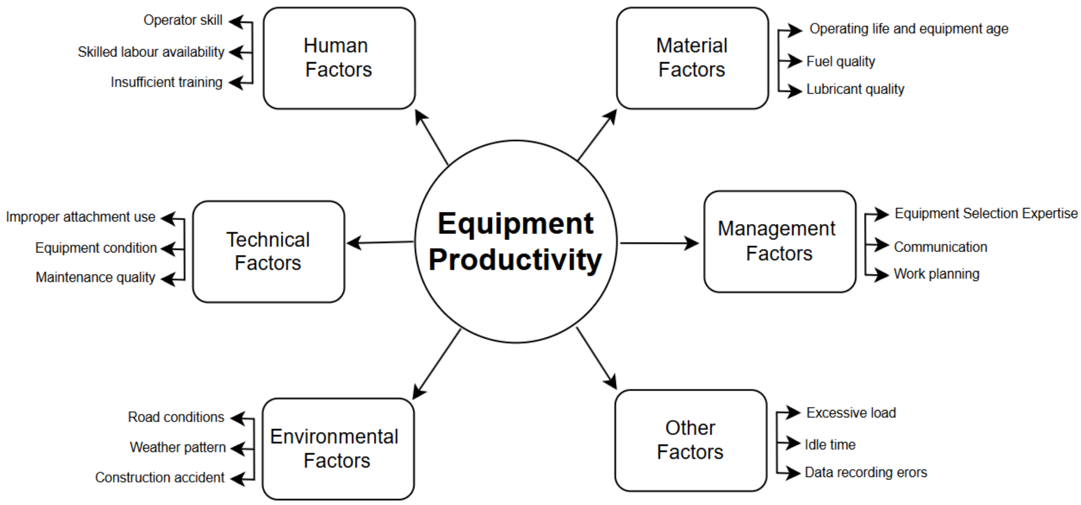


**Figure 1**: Factors affecting equipment productivity in construction.

While Salem et al. (2017) emphasized physical conditions and equipment maintenance and Deokar and Kulkarni (2018) focused on site-based observations, their findings may have limited generalizability due to the localized scope of their study, newer studies integrate broader categories including environmental and managerial factors, suggesting a need for holistic productivity models. This progression reflects a shift from micro-level equipment variables to macro-level operational influences.

2.1.1 Technology driven productivity factors

Recent advancements in Artificial Intelligence (AI), Internet of Things (IoT), and predictive analytics have significantly influenced construction equipment productivity(Anumba and Khallaf, 2022). AI algorithms can forecast equipment maintenance needs, optimize usage schedules, and reduce idle time (Abioye et al., 2021; Alaloul et al., 2020; Lim et al., 2024; Zhang and Jiang, 2024). IoT devices enable real-time monitoring of machinery health, usage patterns, and operational efficiency. Predictive analytics offers foresight into project delays and equipment failures, enabling proactive interventions (Khan et al., 2022).

Automation and robotics are increasingly utilized in repetitive, hazardous, or precision-intensive construction tasks. Examples include autonomous earthmoving, brick-laying robots, and 3D printing for concrete structures. These systems reduce labor dependency and improve consistency in output(Bilal et al., 2016; Chen et al., 2022). Robotics also support real-time error detection and correction during construction, enhancing overall quality (Bock, 2015; Parascho, 2023).

## 2.2 Evolution of Studies in Methodologies of Equipment Productivity Study

The methodologies used to study equipment productivity in construction have evolved significantly over the years, reflecting advancements in technology and data analysis techniques. Early studies, such as those by Salem et al. (2017), relied heavily on questionnaire-based surveys and fuzzy set theory to convert expert linguistic evaluations into numerical values. This approach allowed for the prioritization of factors affecting productivity and served as an early warning system for contractors (Salem et al., 2017). As technology advanced, researchers began to explore more sophisticated methods. Zhu, Ren, and Chen (2017) introduced a vision-based framework integrating detection and tracking techniques to enhance the identification of workforce and equipment from construction jobsite videos. This method significantly improved recall rates by 30–50% while maintaining high precision, offering valuable insights into jobsite productivity and safety monitoring (Zhu et al., 2017).

In 2020, Kim and Chi introduced a multi-camera vision-based approach for monitoring the productivity of earthmoving equipment. This method achieved a high tracking accuracy of 97.6%, significantly improving productivity monitoring compared to single-camera methods. The ability to continuously track equipment movements enhanced decision-making in project management, particularly in optimizing resource allocation and estimating project duration and costs (Kim and Chi, 2020). The advent of deep learning and IoT further revolutionized the field. Mahamedi et al. (2021) proposed an automated method for measuring equipment productivity using smartphone sensors and deep learning algorithms. Their approach achieved an accuracy of 99.78% in productivity measurement, highlighting the effectiveness of deep learning models in classifying equipment states (Mahamedi et al., 2021). Similarly, Kassem et al. (2021) developed a Deep Neural Network (DNN) model to estimate excavator productivity, achieving an $R^2$ value of 0.87. The study introduced an excavation rate as a benchmarking metric, allowing performance comparisons at multiple levels (Kassem et al., 2021).

Recent advancements in equipment productivity studies have been driven by the integration of digital technologies, automation, and predictive analytics. The CIB W78 Conference (2019) highlighted the role of digital technologies in improving construction equipment productivity. The study explored emerging trends such as automation, real-time data collection, and predictive maintenance, emphasizing that integrating digital tools with construction equipment management could lead to enhanced productivity, reduced downtime, and improved project performance (Kassem et al., 2019). In 2021, Mahamedi et al. demonstrated the potential of deep learning models, including Deep Neural Networks (DNN) and Convolutional Neural Networks (CNN-LSTM), in accurately classifying equipment states based on kinematic and noise data collected from smartphones. This low-cost, simple-to-implement approach significantly enhanced the monitoring and benchmarking of equipment productivity in large construction projects (Mahamedi et al., 2021). Kassem et al. (2021) further advanced the field by developing a DNN model to estimate excavator productivity, achieving an $R^2$ value of 0.87. The study introduced an excavation rate as a benchmarking metric, allowing performance comparisons at multiple levels, from individual equipment to whole sites (Kassem et al., 2021).

In 2024, Mansouri Asl et al. proposed a high-level conceptual framework for continuous productivity improvement, critiquing conventional productivity measurement methods for overlooking interconnected factors. The study advocated for a more comprehensive approach that includes productivity estimation, measurement, and factor analysis, stressing the need for standardization in productivity management methodologies (Mansouri Asl et al., 2024). Hajji et al. (2024) developed a combined productivity model for heavy construction equipment (HCE) in a South Trans-Java railroad construction project. Using multiple linear regression analysis, the study estimated the combined productivity rate of excavators and dump trucks, finding an average productivity rate of 35.84 $m^3$/hour under good and moderate field conditions. The model provided a predictive tool for estimating productivity and highlighted the importance of proper equipment allocation for optimal efficiency (Hajji et al., 2024). Finally, Chaure et al. (2024) emphasized the importance of structured equipment management policies, including proactive maintenance protocols and optimized utilization, to improve construction productivity. The study highlighted that equipment breakdowns contribute to nearly 40% of total project overrun costs, underscoring the need for proper equipment selection, routine maintenance, and the adoption of innovative technologies such as IoT and automation (Chaure et al., 2024).

Although Mahamedi et al. (2021) achieved high accuracy using deep learning, the model's scalability and real-time deployment in diverse field conditions require further validation. Similarly, vision-based tracking methods, while precise, face challenges in occlusion and lighting variability on construction sites (Kim and Chi, 2020; Zhu et al., 2017).

### 2.3 Research gaps

There have been advances in the study of equipment production in construction and the application of AI-driven monitoring, predictive maintenance and digital integration, certain gaps do exist. These include:

- A lack of standardized frameworks for comparison of productivity across different equipment types and geographic regions.
- Limited adoption of advanced monitoring tools in small- to mid-scale construction firms due to cost and technical barriers.
- Insufficient research on the impact of environmental sustainability practices on equipment productivity.
- Underexplored integration of AI techniques for real-time optimization of equipment productivity(Eber, 2020;Razi et al., 2023).

## 3. Conclusion

The study of equipment productivity in construction has evolved significantly over the years, driven by advancements in technology, data analysis techniques, and the growing need for efficiency in construction projects. From early reliance on questionnaire-based surveys and fuzzy set theory to the integration of advanced technologies like IoT, deep learning, and predictive analytics, the methodologies used to measure and improve equipment productivity have become increasingly sophisticated. Early studies focused on identifying key factors like equipment age, operator skill, and environmental conditions, providing a foundation for understanding productivity challenges. As technology progressed vision-based frameworks and multi-camera systems introduced, significantly improving the accuracy of productivity monitoring. The advent of deep learning and IoT further revolutionized the field demonstrating the potential of automated, data-driven approaches to enhance equipment productivity.

Recent advancements, such as the development of combined productivity models and the proposal of comprehensive frameworks, have emphasized the importance of integrating historical data, predictive analytics, and standardized methodologies for continuous productivity improvement. These studies highlight the critical role of proper equipment management, proactive maintenance, and the adoption of innovative technologies in reducing downtime and optimizing resource allocation.

The areas in which future enhancements can be made are:

1. Integration of AI and Machine Learning: Future research should focus on further integrating AI and machine learning algorithms to predict equipment failures and optimize maintenance schedules, reducing downtime and improving productivity.
2. Real-Time Monitoring Systems: Developing real-time monitoring systems using IoT and advanced sensors can provide instant feedback on equipment performance, enabling quicker decision-making and resource allocation.
3. Sustainable Practices: Future studies should explore the integration of sustainable practices and green technologies in equipment management, focusing on reducing environmental impact while maintaining high productivity levels.
4. Collaborative Platforms: Developing collaborative platforms where data from multiple construction sites can be shared and analyzed can provide valuable insights and best practices for improving equipment productivity on a larger scale.

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