iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VIII **Month of publication:** August 2026

DOI: https://doi.org/10.22214/ijraset.2026.84635

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

Seismic Vulnerability Assessment and Retrofit Verification of Public Service Buildings in a Himalayan Region: Rapid Visual Screening and ETABS-Based Structural Validation

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Abstract: Public service buildings such as hospitals and schools are critical to community resilience in earthquake-prone Himalayan regions, yet a large proportion of this infrastructure consists of aging and non-engineered construction. This study presents a data-oriented seismic vulnerability assessment of 19 public sector buildings, comprising hospitals and educational institutions, using Rapid Visual Screening (RVS) supported by detailed field surveys.

The assessed buildings include multiple structural blocks constructed between 1919 and 2015, representing unreinforced masonry: BM-brick masonry, HD-half-dressed stone masonry, RR-random rubble masonry, reinforced cement concrete (RCC), and hybrid structural systems.

The assessment integrates building typology, year of construction, occupancy, observed structural and non-structural distress, and the presence or absence of seismic-resistant features, following FEMA P-154 and Indian Standards (IS 1893, IS 4326, IS 13935).

Results indicate that a substantial majority of the surveyed buildings fall within moderate to high seismic vulnerability categories, with unreinforced masonry structures showing the poorest performance. Common deficiencies recorded across the dataset include the absence of seismic bands and vertical reinforcements, extensive horizontal, vertical, and diagonal cracking, severe dampness from foundation level, material degradation, and poor connectivity between structural elements. Even newer RCC and hybrid buildings demonstrated moderate vulnerability due to inadequate detailing, corrosion of reinforcement, and unanchored non-structural components.

To quantitatively verify the effectiveness of the retrofit measures recommended by the RVS-based assessment, two representative structural typologies identified as high-risk in the survey- a three-storey (G+2) RC framed building with masonry infill and a two-storey (G+1) masonry building—were further evaluated through detailed linear structural modelling and analysis in ETABS, in accordance with IS 456:2000 and IS 13920:2016. The retrofit schemes evaluated (column section jacketing for the G+2 RC frame, and lateral stiffening for the G+1 masonry structure) produced substantial improvements: storey drift and displacement reduced by up to 94%, storey stiffness increased by up to about 20 times, and all previously over-stressed columns (demand/capacity ratio >1.0) were brought within safe design limits (0.33–0.74) after retrofitting.

The study establishes a clear, data-based relationship between construction typology, age, observed distress, and seismic vulnerability, and demonstrates through structural analysis that the recommended retrofit interventions are effective in achieving code-compliant seismic performance. The findings confirm that RVS is an effective and scalable tool for prioritizing seismic retrofitting of public buildings, and that the proposed retrofit strategies are structurally verifiable using standard analysis software. The results underscore the urgent need for code-compliant retrofitting and maintenance interventions to reduce seismic risk and ensure life safety and post-disaster functionality of critical public infrastructure in Himalayan seismic zones.

Keywords: Seismic vulnerability, Rapid Visual Screening, unreinforced masonry, Himalayan region, Retrofitting, Column jacketing.

I. INTRODUCTION

Earthquakes represent a major natural hazard in the Himalayan region due to active tectonics, high strain accumulation, and complex geological conditions. Northern India lies along the collision boundary of the Indian and Eurasian plates and has experienced several destructive earthquakes in the past, including the 1905 Kangra earthquake and subsequent moderate-to-strong seismic events that caused widespread damage to the built environment (Middlemiss, 1910; NDMA, 2014). In this seismically active context, the safety and functionality of public service buildings, particularly hospitals and schools, are of paramount importance, as these structures are expected to remain operational during and after earthquakes.

Despite continuous advancement in earthquake-resistant design philosophy and the development of national seismic codes in India, a large proportion of the existing building stock remains highly vulnerable. Many public buildings were constructed prior to the introduction or enforcement of modern seismic provisions such as IS 1893 (Part 1):2016 for seismic loading and IS 4326:1993 for earthquake-resistant construction. Furthermore, even buildings constructed after the introduction of seismic codes often suffer from inadequate compliance, poor workmanship, and lack of professional engineering supervision, particularly in rural and semi-urban Himalayan regions (Murty et al., 2014; Sawhney, 2014). Unreinforced masonry (URM) buildings dominate the construction landscape in Himalayan states, owing to the availability of local materials, traditional construction practices, and economic constraints. These structures are commonly built using brick masonry, half-dressed stone masonry, or random rubble masonry bonded with mud, lime, or weak cement mortar. From a seismic perspective, URM buildings are inherently brittle and exhibit poor lateral load resistance due to the absence of confinement, weak interlocking between structural elements, and lack of ductility (IS 4326:1993). In addition to structural deficiencies, environmental and durability-related issues significantly influence seismic performance. Field investigations across Himalayan regions reveal widespread dampness, moisture ingress, biological growth, and material degradation in masonry buildings. Persistent moisture weakens mortar joints, reduces masonry stiffness, accelerates cracking, and increases mass irregularity, thereby amplifying seismic vulnerability (Amiraslanzadeh et al., 2012). These effects are particularly critical in older public buildings that have received limited maintenance over long service lives.

Given the vast number of existing buildings and limited technical and financial resources, it is neither feasible nor necessary to conduct detailed structural analysis for every structure. Consequently, seismic vulnerability assessment is commonly carried out using a tiered approach, where Rapid Visual Screening (RVS) serves as the first level of evaluation. RVS is a field-based method that relies on observable structural, architectural, and site characteristics to identify buildings that are potentially hazardous and require further detailed evaluation or retrofitting (FEMA, 2015). In India, RVS-based assessment is supported by IS 13935:2009, which provides guidelines for seismic evaluation and strengthening of existing buildings.

In this context, the present study undertakes a data-oriented seismic vulnerability assessment of public hospitals and schools located in a seismically active Himalayan region. The study is based on detailed field surveys of 19 public sector buildings, comprising multiple structural blocks constructed between 1919 and 2015. The dataset captures a wide range of construction typologies, including unreinforced masonry, reinforced cement concrete (RCC), and hybrid systems, along with variations in age, occupancy, material condition, and maintenance. The assessed buildings serve critical social functions and accommodate large daily populations, making their seismic performance a key concern for disaster risk reduction.

The primary objective of this research is to evaluate seismic vulnerability using empirical field data obtained through Rapid Visual Screening, focusing on parameters such as structural system type, plan and vertical irregularities, presence of seismic-resistant features, observed cracking patterns, dampness, and non-structural hazards. By establishing clear relationships between observed deficiencies and seismic risk, the study aims to provide a robust evidence base for prioritizing retrofitting interventions in accordance with IS 13935. To move beyond qualitative prioritization, the study further undertakes detailed structural modelling and analysis in ETABS for two representative building typologies flagged as high-risk during the screening- a G+2 RC framed structure with masonry infill and a G+1 masonry structure- in order to quantitatively verify the structural adequacy of the proposed retrofit measures. The outcomes of this research are intended to support engineers, planners, and local authorities in strengthening public infrastructure and enhancing seismic resilience in Himalayan regions.

II. STUDY AREA AND BUILDING INVENTORY

The study focuses on public service buildings located in a seismically active Himalayan district falling within Seismic Zone IV as per IS 1893 (Part 1):2016. The dataset consists of 19 public service buildings, including:

1) Hospitals: Multi-block facilities with bed capacities of approximately 50–100.
2) Schools: Government primary, secondary, and senior secondary schools with multiple blocks.

Each facility comprises between 1 and 7 structural blocks, resulting in a diverse dataset of masonry, RCC, and hybrid constructions.

A. Surveyed Buildings

The dataset used in this study comprises 19 public service buildings, selected due to their high occupancy, social importance, and critical role during post-earthquake emergency response. The surveyed buildings include public hospitals and government educational institutions, representing essential infrastructure within the study region. These facilities were chosen to reflect a realistic cross-section of existing public building stock in a seismically active Himalayan environment.

The hospital buildings consist of multi-block healthcare facilities with bed capacities ranging approximately between 50 and 100 beds. These hospitals serve large rural and semi-urban populations and are required to function continuously during disaster scenarios. Most hospital campuses comprise multiple blocks constructed during different periods, resulting in variations in structural systems, material quality, and construction practices within the same facility.

The educational buildings include government primary, secondary, and senior secondary schools, accommodating students from early schooling through higher secondary education. These schools typically experience high daytime occupancy and often function as emergency shelters during disasters. Similar to hospitals, school campuses generally consist of multiple blocks, added incrementally over time to meet growing educational demands. The number of blocks per facility varies from one to seven, creating a heterogeneous building inventory with significant variation in age, height, and construction quality.

Across the dataset, buildings range in construction age from early twentieth century structures to buildings constructed as recently as 2015. This wide temporal span captures the evolution of construction practices from traditional, non-engineered masonry systems to more recent reinforced concrete and hybrid constructions. The dataset therefore provides a comprehensive empirical basis for evaluating how age, construction typology, and maintenance condition influence seismic vulnerability.

B. Construction Typology Distribution

Based on detailed field surveys and visual inspections, the buildings were classified into five primary construction typologies:

1) Half-dressed stone masonry
2) Random rubble masonry
3) Brick masonry
4) Reinforced Cement Concrete (RCC) structures
5) Mixed (hybrid) systems, combining masonry and RCC elements

The analysis reveals that older building blocks constructed before 1990 are predominantly unreinforced masonry, including half-dressed stone masonry, random rubble masonry, and brick masonry. These structures typically lack engineered design input and were constructed using locally available materials and traditional techniques. Common characteristics include thick load-bearing walls, weak mortar, absence of seismic bands, and minimal connectivity between structural components, all of which adversely affect seismic performance.

Buildings constructed after 2000 show a gradual shift toward RCC and hybrid construction systems, particularly in newly added blocks within hospital and school campuses. However, field observations indicate that many of these newer buildings still exhibit deficiencies in seismic detailing, such as inadequate reinforcement anchorage, poor beam-column joint detailing, and lack of ductile design provisions. In several cases, RCC frames are combined with unreinforced masonry infill or masonry load-bearing walls without proper integration, resulting in hybrid systems that remain vulnerable during seismic loading.

Mixed construction systems are particularly common where older masonry blocks have been extended or vertically augmented using RCC elements. Such incremental development has introduced plan and vertical irregularities, stiffness discontinuities, and stress concentration zones, increasing overall seismic vulnerability.

Overall, the construction typology distribution highlights that while material transitions toward RCC are evident in newer constructions, non-engineered practices and lack of seismic compliance persist across all age groups. This underscores the importance of systematic vulnerability assessment and retrofitting not only for older masonry buildings but also for relatively newer RCC and hybrid structures.

III. METHODOLOGY

A. Rapid Visual Screening (RVS)

The methodology adopted in this study is based on a parameter-driven Rapid Visual Screening (RVS) framework, wherein each building is evaluated through a predefined set of structural, architectural, environmental, and functional indicators that collectively influence seismic performance. The structural system and material type form the base parameter, as they define the inherent strength, stiffness, and ductility of the building. Masonry, RCC, and hybrid systems were therefore treated separately during evaluation.

The number of storeys and vertical irregularities were assessed to capture potential dynamic amplification and discontinuities in load transfer. Buildings with sudden changes in stiffness or mass were flagged due to their known susceptibility to concentration of seismic damage. Plan irregularity and mass distribution were examined to identify torsional vulnerability arising from asymmetric layouts or uneven mass placement.

The presence or absence of seismic bands and vertical reinforcements was evaluated as a direct indicator of code compliance and seismic resistance, particularly for masonry buildings. Visible structural distress, such as cracking, settlement, and corrosion, was recorded as empirical evidence of existing weakness and reduced load-carrying capacity. Moisture ingress and material degradation were included due to their long-term impact on structural integrity, especially in aging masonry.

Finally, site conditions and slope effects were considered to account for demand amplification, while occupancy and functional importance were integrated to prioritize buildings with high life-safety and post-earthquake relevance. Together, these parameters provided a systematic and reproducible basis for seismic vulnerability classification.

B. Building Inventory and Data Classification

Prior to seismic vulnerability assessment, a structured building inventory was prepared to ensure consistent application of the Rapid Visual Screening methodology. Each facility was identified and subdivided into structural blocks where phased construction was observed. Buildings were classified based on construction typology, construction period, number of blocks, and functional use using direct visual inspection and available records. This preliminary classification provided a uniform dataset for subsequent vulnerability evaluation. The summarized classification of surveyed buildings is presented in Table 1.

Table 1: Summary of Building Construction Typology, Construction Period, and No. of Blocks

Construction Typology	Typical Construction Period	No. of Blocks per Facility	Predominant Building Use	Key Observed Characteristics
Half-dressed Stone Masonry	1919–1995	1–7	Hospitals, Schools	Thick load-bearing walls; weak/deteriorated mortar; absence of seismic bands; severe dampness and cracking
Random Rubble Masonry	1950–1990	1–5	Schools, Older Hospital Blocks	Irregular stone layout; poor interlocking; lack of vertical reinforcement; diagonal and horizontal cracks
Brick Masonry	1960–2015	1–6	Schools, Hospital Extensions	Moderate wall thickness; high opening ratios; no seismic detailing; moisture-induced plaster deterioration
RCC Structures	2005–2015	1–3	Hospitals, Schools	Improved material strength but inadequate ductile detailing; corrosion in some members; soft-storey conditions in places
Mixed (Hybrid) Systems	1975–2015	2–7	Hospitals, Schools	Masonry walls combined with RCC beams/frames; stiffness discontinuity; poor interface detailing; plan and vertical irregularities

C. Structural Modelling and Analysis Using ETABS

While Rapid Visual Screening provides a rapid, field-based prioritization of seismic risk, it does not by itself quantify the structural adequacy of a specific retrofit intervention. To bridge this gap, two representative structural typologies identified as high-risk during the RVS survey were selected for detailed linear structural modelling and analysis using ETABS, a widely used finite-element based structural analysis and design software: (i) a three-storey (Ground + 2 upper floors, “G+2”) reinforced concrete framed building with masonry infill walls, representative of the RCC and hybrid typologies in the inventory, and (ii) a two-storey (Ground + 1 upper floor, “G+1”) masonry building, representative of the unreinforced masonry typologies. Both structures were analysed in their existing (as-built, non-retrofitted) configuration and in a proposed retrofitted configuration, in accordance with IS 456:2000 and IS 13920:2016.

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For the G+2 RC framed structure, the retrofit measure consisted of column section jacketing- enlarging the column cross-section and upgrading the concrete grade- targeted at columns found to be over-stressed (demand/capacity ratio greater than 1.0) under the governing seismic load combinations. For the G+1 masonry structure, the retrofit measure consisted of a lateral stiffening intervention intended to substantially increase the lateral stiffness of the structure and thereby reduce its seismic displacement and drift response. In both cases, the structural response parameters compared between the existing and retrofitted configurations were maximum storey displacement, maximum storey drift, storey shear, and storey stiffness, evaluated in both principal (X and Y) directions. For the G+2 structure, member-level design checks (demand/capacity ratios) were additionally carried out for all columns to identify specific structural deficiencies and verify their resolution after retrofitting. The detailed structural models, result plots, and design check outputs are presented in Section 4.3.

IV. RESULTS

A. Structural Vulnerability Distribution and Damage Characteristics

The Rapid Visual Screening (RVS) results reveal a pronounced concentration of seismic vulnerability among masonry buildings, particularly unreinforced masonry (URM) structures. A majority of URM buildings were classified as high-risk, whereas RCC and hybrid buildings generally fall within moderate-risk categories. This distinction is primarily attributed to differences in structural systems, detailing practices, and material behaviour under seismic loading.

One of the most significant findings is the widespread absence of seismic bands in masonry buildings, including plinth, lintel, and roof bands, which are essential for ensuring box action. Additionally, vertical reinforcement at corners, junctions, and openings was largely missing, making masonry walls susceptible to separation and out-of-plane failure. Incremental and unplanned construction has resulted in frequent plan and vertical irregularities, such as re-entrant corners and stiffness discontinuities, further amplifying seismic demand. Material degradation, particularly in older stone masonry buildings, was found to strongly influence vulnerability scores.

Damage pattern analysis highlights consistent trends across building typologies. In masonry buildings, the dominant indicators include horizontal cracks at lintel and sill levels, vertical cracks at wall junctions, and diagonal shear cracks in load-bearing walls. Severe rising dampness from foundations, along with peeling plaster and surface disintegration, was observed in almost all older masonry blocks. These defects are directly associated with poor seismic performance modes, including loss of box action, in-plane shear failure, and out-of-plane wall collapse.

RCC buildings demonstrated comparatively better global stability; however, several critical deficiencies were observed. These include poor reinforcement detailing, loss of concrete cover, and corrosion of reinforcement due to moisture ingress. In some buildings, soft-storey conditions were created by open ground floors, while unanchored non-structural elements, such as water tanks and parapets, posed additional life-safety hazards. Hybrid buildings exhibited stress concentration at masonry-RCC interfaces, increasing the likelihood of localized damage and partial failure during seismic events.

Moisture-induced degradation emerged as a key aggravating factor across all typologies. Buildings with persistent dampness showed reduced material strength, accelerated crack propagation, and increased mass irregularity, leading to brittle failure behaviour, particularly in stone masonry structures. When combined with high occupancy levels in hospitals and schools- often housing hundreds of occupants daily- the observed structural vulnerabilities significantly elevate seismic risk and potential casualty levels.

Table 2: Details of Surveyed Hospitals and Schools -Construction Characteristics and Observed

Category	Name & Location	Blocks	Year(s) Established	Construction Type	Observed Defects
Hospitals	Hospital 1	4 (A–D)	1992–2000	A & D: HD stone masonry; B: HD stone + brick; C: RCC	Severe dampness, major cracks, peeling plaster
	Hospital 2	1 (A)	1990–2004	HD stone masonry + brick	Severe dampness, major cracks, peeling plaster
	Hospital 3	3 (A–C)	1975–1990	A & B: Random rubble + HD stone; C: HD stone	Severe dampness, major cracks, peeling plaster
	Hospital 4	2 (A–B)	2012–2014	Both RCC	Severe dampness, major

					cracks, peeling plaster
	Hospital 5	2 (A–B)	2007, 1922	A: RCC; B: HD stone masonry	Severe dampness, major cracks, peeling plaster
	Hospital 6	1 (A)	1990	HD stone masonry	Severe dampness, major cracks, peeling plaster
	Hospital 7	2 (A–B)	1999, 1983	Both HD stone masonry	Severe dampness, major cracks, peeling plaster
	Hospital 8	3 (A–C)	1990–2010	All HD stone masonry	Severe dampness, major cracks, peeling plaster
	Hospital 9	3 (A–C)	1919, 1920, 2005	A & B: HD stone masonry; C: RCC	Severe dampness, major cracks, peeling plaster
Schools	School 1	7 (A–G)	1962, 2008, 2012, 1990, 1987	A & B: HD stone; C & E: RCC; D: Brick; F & G: HD stone + brick	Severe dampness, major cracks, peeling plaster
	School 2	3 (A–C)	1960, 1993, 2014	A: HD stone; B: Brick; C: RCC	Severe dampness, major cracks, peeling plaster
	School 3	5 (A–E)	2015, 2000, 2012, 1960	A: Brick; B: RR + HD stone + brick; C: RR + brick; D: RR; E: HD stone	Severe dampness, major cracks, peeling plaster
	School 4	3 (A–C)	2012, 1952, 2009	A & C: Brick; B: RCC	Severe dampness, major cracks, peeling plaster
	School 5	4 (A–D)	1996, 2014, 2015, 1985	A: Brick; B & C: RCC; D: HD stone	Severe dampness, major cracks, peeling plaster
	School 6	7 (A–G)	2007, 1954, 1997, 1993, 2015, 1970, 1998	A: RCC; B: HD stone; C: Brick; D: RCC; E: HD stone; F: Brick; G: RCC	Severe dampness, major cracks, peeling plaster
	School 7	4 (A–D)	2005, 1992, 2010, 1978	A: RCC; B: Brick; C: RCC; D: HD stone	Severe dampness, major cracks, peeling plaster
	School 8	3 (A–C)	2012, 1985, 2001	A: RCC; B: Brick; C: HD stone	Severe dampness, major cracks, peeling plaster
	School 9	2 (A–B)	2009, 1975	A: RCC; B: HD stone	Severe dampness, major cracks, peeling plaster
	School 10	5 (A–E)	2011, 1980, 1995, 2003, 1972	A: RCC; B: Brick; C: HD stone; D: RCC; E: Brick	Severe dampness, major cracks, peeling plaster

Defects (HD = Half-dressed stone; RR = Random rubble)

B. Typology-Wise Seismic Vulnerability in the Context of Indian Seismic Codes

The typology-wise vulnerability assessment of the surveyed hospitals and schools demonstrates a strong correlation between construction system and seismic performance, consistent with the provisions and intent of IS 4326:1993 and IS 13935:2009. URM buildings including HD stone masonry, RR masonry, and BM exhibit the highest vulnerability levels, primarily due to non-compliance with basic earthquake-resistant construction requirements prescribed in IS 4326.

IS 4326 emphasizes the critical role of horizontal seismic bands at plinth, lintel, and roof levels, as well as vertical reinforcement at corners, junctions, and around openings, to ensure adequate box action and ductility in masonry buildings. The field data reveal that a majority of URM structures lack these essential features, directly explaining the observed damage patterns such as diagonal shear cracking, wall separation, and out-of-plane failure. RR masonry buildings, in particular, show severe vulnerability due to irregular stone arrangement and poor interlocking, which are explicitly identified in IS 4326 as unfavourable for seismic resistance unless properly confined.

Brick masonry buildings demonstrate slightly improved performance compared to stone masonry; however, high opening ratios and absence of codal detailing significantly reduce lateral load capacity. According to IS 13935, such deficiencies necessitate structural strengthening measures, including reinforced concrete bands, vertical steel reinforcement, and wall stitching, especially in buildings of high functional importance.

Reinforced cement concrete (RCC) buildings in the dataset generally fall within moderate vulnerability categories. While RCC framing systems inherently provide better seismic resistance, IS 13920-compliant ductile detailing is often absent, resulting in deficiencies such as poor beam-column joint performance and soft-storey behaviour. IS 13935 identifies these conditions as requiring detailed evaluation and retrofitting, particularly for buildings with open ground floors or corrosion-induced strength loss.

Mixed (hybrid) construction systems exhibit compounded vulnerabilities due to stiffness discontinuities and weak masonry-RCC interfaces, which are highlighted in IS 13935 as critical concerns in incrementally constructed buildings. Stress concentration at these interfaces increases the likelihood of localized damage and partial collapse.

Overall, the typology-wise vulnerability summary reinforces the necessity of prioritized retrofitting of URM and hybrid buildings in accordance with IS 13935 guidelines, particularly for hospitals and schools where occupancy-related risk is high. The findings confirm that compliance with basic codal provisions remains the most effective means of reducing seismic vulnerability in existing public infrastructure.

In accordance with IS 13935:2009, the retrofit strategies presented in Table 3 directly address the main vulnerability mechanisms identified through Rapid Visual Screening. The structural adequacy of representative retrofit interventions from this table- column jacketing for RCC structures and lateral stiffening for masonry structures- is further verified through ETABS structural analysis in Section 4.3.

Table 3: Typology-Wise Seismic Retrofit Strategy Mapping Based on IS 13935

Construction Typology	Observed Vulnerability (from RVS)	Key Codal Deficiencies (IS 4326 / IS 13935)	Recommended Retrofit Interventions (IS 13935)	Priority Level
HD Stone Masonry (URM)	High	Absence of seismic bands; no vertical reinforcement; weak mortar; loss of box action	RC bands at plinth, lintel, and roof levels; vertical steel reinforcement at corners and junctions; wall stitching; grout injection; diaphragm anchorage	Very High
RR Masonry (URM)	High	Poor interlocking; irregular geometry; lack of confinement	RC bands and splints; reinforced concrete jacketing at critical walls; mesh reinforcement with shotcrete; foundation strengthening where required	Very High
BM (URM)	High to Moderate	High opening ratios; inadequate lintel/sill bands; moisture-related degradation	RC lintel and sill bands; vertical reinforcement near openings; crack stitching; masonry strengthening using welded wire mesh	High
RCC Structures	Moderate	Inadequate ductile detailing; corrosion; soft-storey conditions	RC jacketing of columns and beams; shear walls or bracings for soft-storey mitigation; corrosion treatment and cover restoration	Moderate
Mixed (Hybrid) Systems	Moderate to High	Masonry-RCC interface weakness; stiffness discontinuity	Interface strengthening using RC bands and connectors; selective jacketing; load path continuity improvement; separation joints where feasible	High

Based on the Rapid Visual Screening results, vulnerability assessment, and codal interpretation, the following retrofitting guidelines are proposed in accordance with IS 13935:2009 and supporting provisions of IS 4326:1993. These guidelines prioritize life safety, functionality, and feasibility for public buildings such as hospitals and schools.

1) Unreinforced Masonry Buildings- Half-dressed stone masonry, random rubble masonry, and brick masonry buildings classified as high-risk should be prioritized for immediate strengthening. Retrofitting measures should include the provision of reinforced concrete (RC) bands at plinth, lintel, and roof levels to restore box action. Vertical steel reinforcement should be introduced at corners, wall junctions, and around openings. Cracked masonry walls should be strengthened using stitching techniques, grout injection, and welded wire mesh with shotcrete, as recommended by IS 13935.
2) Random Rubble Masonry Structures- Due to poor interlocking and irregular geometry, additional confinement is essential. RC splints, jacketing of critical walls, and foundation strengthening should be considered where significant settlement or instability is observed.
3) RCC Buildings- Buildings exhibiting moderate vulnerability require ductility enhancement through RC jacketing of columns and beams, strengthening of beam-column joints, and mitigation of soft-storey effects using shear walls or bracing systems. Corrosion-damaged members must undergo repair, cover restoration, and durability treatment.
4) Hybrid (Masonry-RCC) Structures- Hybrid buildings require special attention at masonry-RCC interfaces. Strengthening measures should focus on improving load-path continuity using RC bands, connectors, selective jacketing, and where feasible, seismic separation joints.
5) Moisture Control and Maintenance- Since moisture-induced degradation significantly amplifies seismic vulnerability, drainage improvement, waterproofing, and regular maintenance should be integrated with all retrofitting interventions.

C. ETABS Structural Validation of Retrofit Measures

This section presents the detailed structural analysis results for the two representative building typologies described in Section 3.3, comparing the existing (as-built, non-retrofitted) structure with the corresponding retrofitted structure in each case. Results are presented topic-wise: structural model, maximum storey displacement, maximum storey drift, storey shear, and storey stiffness, followed by member-level design checks where applicable.

1) Case Study A: G+2 RC Framed Structure with Masonry Infill

The building considered for this case study is a G+2 (three-storey) reinforced concrete framed structure with masonry infill walls, modelled and analysed in ETABS 22.0.0 in accordance with IS 456:2000 and IS 13920:2016. The building is laid out on a grid of 6 column lines (A–F) in the X-direction with a typical bay width of 3.65 m, and 4 column lines (1–4) in the Y-direction with bay widths of 6.0 m and 3.45 m. The storey heights are 3 m each for the Ground, First and Second floors, giving a total building height of 9 m. Columns were originally designed as 450 mmx450 mm sections in M15 grade concrete with Fe415 reinforcement. The lateral load resisting system consists of ductile RC moment frames as per IS 13920:2016.

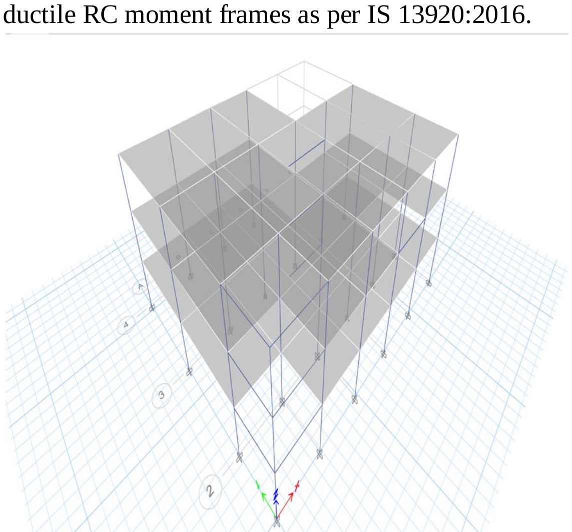

Fig. 1: 3D Extruded View of the ETABS Structural Model (G+2 Structure)

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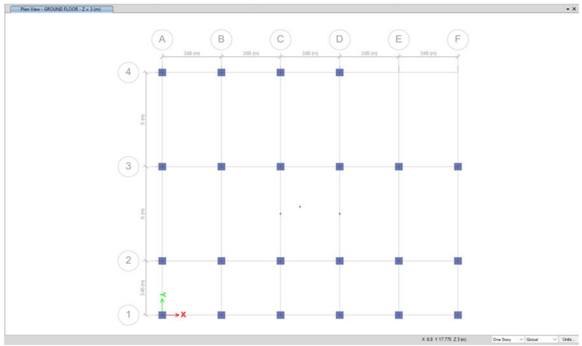


Fig. 2: Plan View of the Structure at Ground Floor Level, Z = 3 m (G+2 Structure)

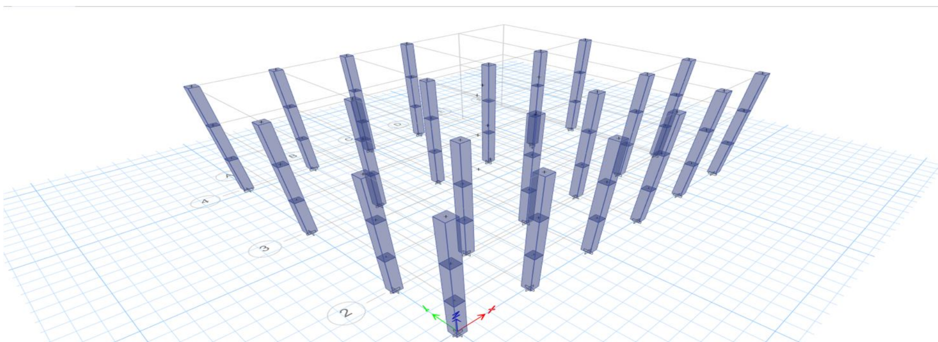


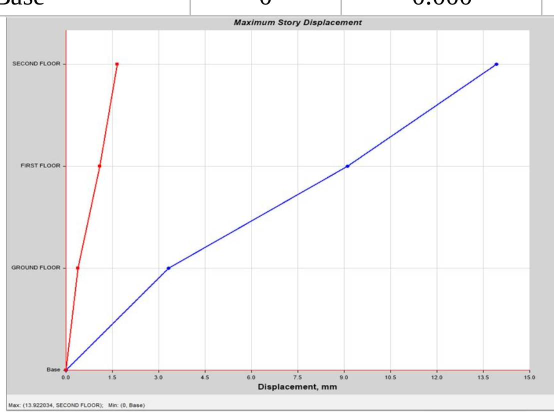
Fig. 3: 3D View of the Column Grid Layout (G+2 Structure)

(a) Maximum Storey Displacement

The maximum lateral storey displacements obtained from ETABS for the existing (non-retrofitted) and the retrofitted structures are summarised in Table 4 and plotted in Figures 4 and 5. The displacement increases from the base to the roof in both cases, following the expected cantilever-type deflected shape of a moment-resisting frame.

Table 4: Maximum Storey Displacement -Existing vs. Retrofitted Structure (G+2)

Storey	Elevation (m)	Existing X-dir (mm)	Existing-Y-dir (mm)	Retrofitted -X-dir (mm)	Retrofitted -Y-dir (mm)
Second Floor	9	13.922	1.661	14.258	1.701
First Floor	6	9.101	1.091	9.340	1.068
Ground Floor	3	3.321	0.390	3.496	0.381
Base	0	0.000	0.000	0.000	0.000



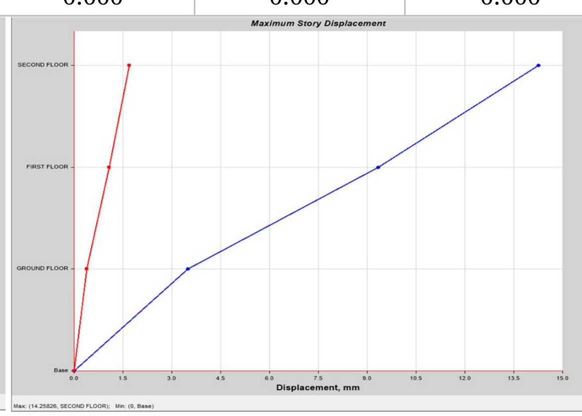


Fig. 4: Maximum Storey Displacement -Existing (Non-Retrofitted) Structure (G+2) Fig. 5: Maximum Storey Displacement - Retrofitted Structure (G+2)

It is observed that the maximum roof displacement increases marginally, from 13.92 mm to 14.26 mm (about 2.4%) in the X-direction, after retrofitting. This small increase is attributable to the higher seismic mass/stiffness redistribution caused by column jacketing, and remains within acceptable serviceability limits.

(b) Maximum Storey Drift

Storey drift is defined as the relative lateral displacement between two consecutive storeys divided by the storey height. As per IS 1893 (Part 1), the allowable storey drift limit is 0.004 times the storey height. The maximum storey drift values for both models are presented in Table 5 and Figures 6 and 7.

Table 5: Maximum Storey Drift -Existing vs. Retrofitted Structure (G+2)

Storey	Elevation (m)	Existing -X-dir	Existing -Y-dir	Retrofitted -X-dir	Retrofitted -Y-dir
Second Floor	9	0.001607	0.000190	0.001639	0.000211
First Floor	6	0.001927	0.000234	0.001948	0.000229
Ground Floor	3	0.001107	0.000130	0.001165	0.000127
Base	0	0.000000	0.000000	0.000000	0.000000

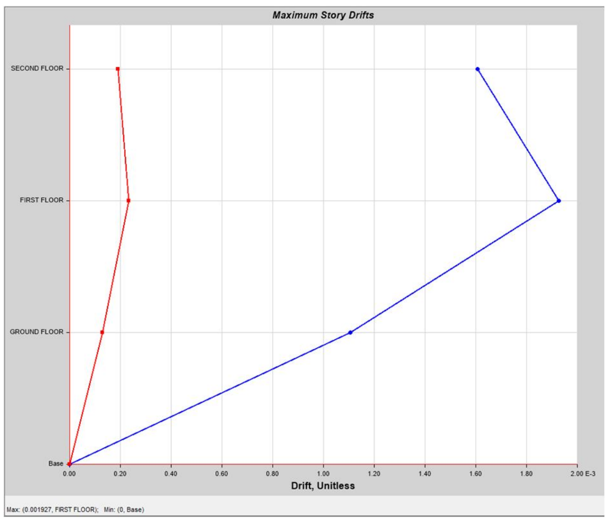


Fig. 6: Maximum Storey Drift -Existing (Non-Retrofitted) Structure (G+2)

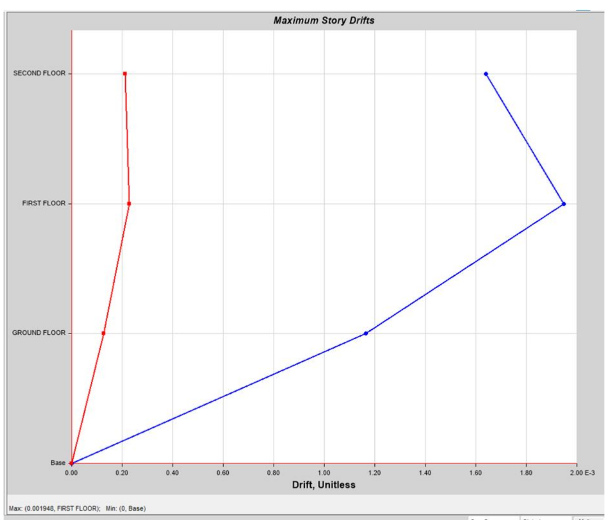


Fig. 7: Maximum Storey Drift -Retrofitted Structure (G+2)

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The maximum drift in both models occurs at the First Floor level (0.001927 for the existing structure and 0.001948 for the retrofitted structure, in the X-direction), which is well below the IS 1893 permissible limit of 0.004. This confirms that both the existing and retrofitted configurations satisfy the serviceability drift criterion.

(c) Storey Shear

The storey shear represents the cumulative lateral force resisted at each storey level and increases from the roof towards the base. Figures 8 and 9 present the storey shear distribution along the height of the building.

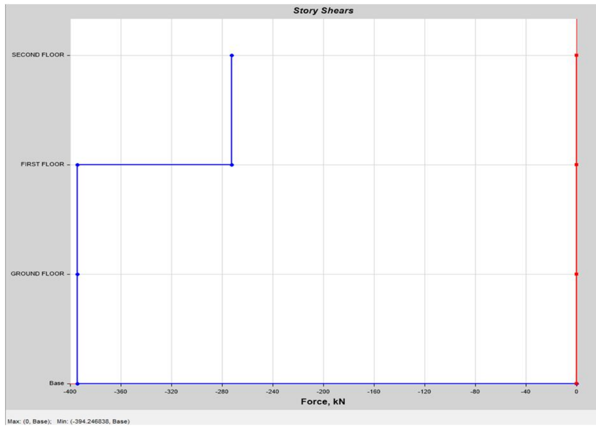

Fig. 8: Storey Shear -Existing (Non-Retrofitted) Structure (G+2)

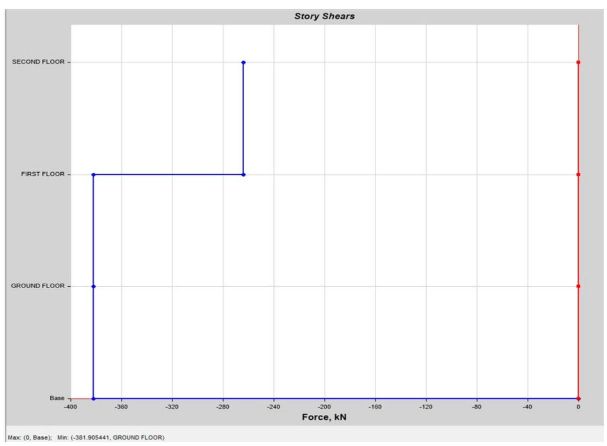

Fig. 9: Storey Shear -Retrofitted Structure (G+2)

The base shear reduces slightly from 394.25 kN (existing) to 381.91 kN (retrofitted). The shear force remains constant between the Ground Floor and First Floor levels in both models, indicating no intermediate lateral load application between these levels.

(d) Storey Stiffness

Storey stiffness reflects the lateral load-resisting capacity of each storey and is calculated as the storey shear divided by the storey drift. The results for both models are given in Table 7 and Figures 10 and 11.

Table 6: Storey Stiffness -Existing vs. Retrofitted Structure (G+2)

Storey	Elevation (m)	Existing (kN/m)	Retrofitted (kN/m)
Second Floor	9	62,320.148	59,725.814
First Floor	6	75,374.876	72,030.450
Ground Floor	3	130,569.691	119,633.353
Base	0	0.000	0.000

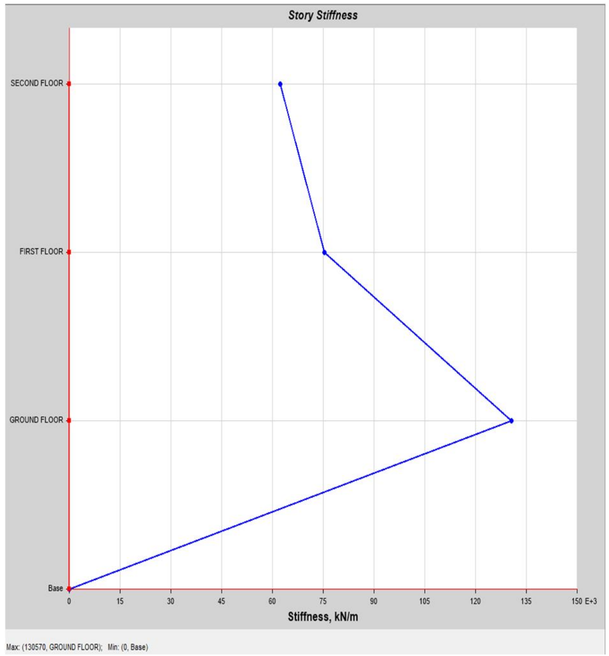

Fig. 10: Storey Stiffness -Existing (Non-Retrofitted) Structure (G+2)

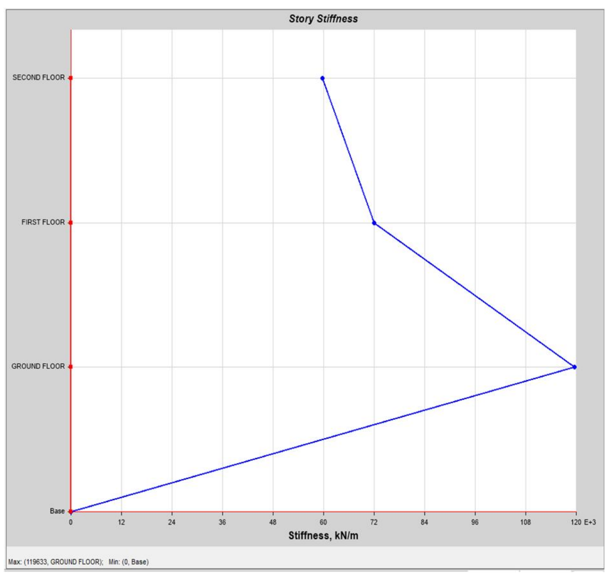

Fig. 11: Storey Stiffness -Retrofitted Structure (G+2)

The Ground Floor exhibits the highest storey stiffness in both models (130,570 kN/m existing; 119,633 kN/m retrofitted), which is expected as it carries the full height of column above it with the shortest effective column length contribution to drift.

(e) Column Design Check and Identification of Deficient Columns

ETABS concrete frame design (IS 456:2000 + IS 13920:2016) was used to check the adequacy of all columns under the governing seismic load combinations. Columns with a Demand/Capacity (D/C) ratio greater than 1.0 are flagged as “Over-stressed (O/S)” and are structurally deficient. Table 8 lists the columns found to be over-stressed in the existing (450 mmx450 mm, M15 concrete) structure, along with their D/C ratio after retrofitting by section jacketing to 550 mmx550 mm using M30 grade concrete.

Table 7: Over-stressed Columns in Existing Structure and Corresponding Retrofitted D/C Ratios (G+2)

Storey	Column ID	Section -Existing	D/C Ratio - Existing	Status - Existing	Section - Retrofitted	D/C Ratio - Retrofitted
Second Floor	C2	450x450 mm	1.009	O/S	550x550 mm	0.367
Second Floor	C3	450x450 mm	1.018	O/S	550x550 mm	0.332
Second Floor	C12	450x450 mm	1.034	O/S	550x550 mm	0.378
Second Floor	C17	450x450 mm	1.021	O/S	550x550 mm	0.340
First Floor	C24	450x450 mm	1.067	O/S	550x550 mm	0.505
Ground Floor	C7	450x450 mm	1.002	O/S	550x550 mm	0.478
Ground Floor	C23	450x450 mm	1.009	O/S	550x550 mm	0.480
Ground Floor	C13	450x450 mm	1.019	O/S	550x550 mm	0.735

All eight columns identified above exceed the permissible D/C ratio of 1.0 in the existing structure, making them critical elements governing the seismic vulnerability of the building. After retrofitting through section enlargement (450 mmx450 mm to 550 mmx550 mm) and upgrading the concrete grade from M15 to M30, all D/C ratios reduce to within the safe range of 0.33–0.74, confirming the adequacy of the proposed retrofitting scheme.

Table 8: Summary of Section and Material Properties -Before and After Retrofitting (G+2)

Parameter	Existing Structure	Retrofitted Structure
Column Section	450 mmx450 mm	550 mmx550 mm
Concrete Grade	M15 (fck = 15 MPa)	M30 (fck = 30 MPa)
Modulus of Elasticity, Ec	19,354.92 MPa	27,386.13 MPa
Reinforcement Grade	Fe415	Fe415
Retrofitting Technique	–	RC Jacketing (Section Enlargement)
Design Codes	IS456:2000, IS 13920:2016	IS 456:2000,IS 13920:2016

The Case Study A results demonstrate that the existing masonry-infilled RC framed structure has eight columns- distributed across the Ground, First and Second floors- that are inadequate to resist the design seismic forces (D/C ratio > 1.0). The proposed jacketing-based retrofitting scheme, involving section enlargement to 550 mmx550 mm and upgrading concrete grade to M30, is shown to bring all deficient columns within safe design limits while storey drift remains within the IS 1893 permissible value of 0.004 for both the existing and retrofitted configurations.

2) Case Study B: G+1 Masonry Structure

This case study presents the structural response of a two-storey (Ground Floor + First Floor) masonry building modelled in ETABS, comparing the existing (as-built, non-retrofitted) structure with a proposed retrofitted structure. As with Case Study A, the parameters compared are maximum storey displacement, maximum storey drift, storey shear, and storey stiffness, evaluated in both the X and Y directions.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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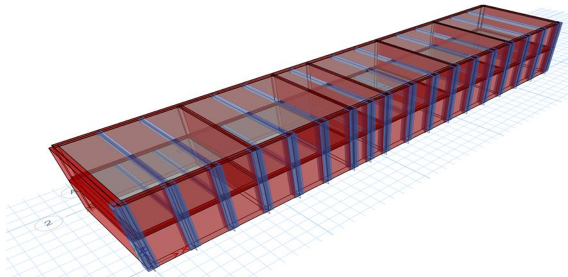

Fig. 13: 3D ETABS Model of Existing (As-Built) Structure (G+1)

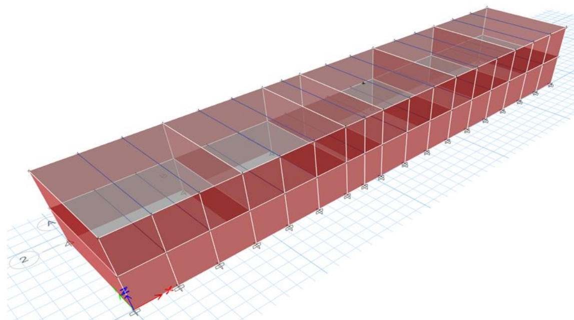

Fig. 14: 3D ETABS Model of Retrofitted Structure (G+1)

(a) Maximum Storey Displacement

The maximum storey displacement was obtained at each level (Base, Ground Floor, 1st Floor) for both principal directions. A substantial reduction in lateral displacement is observed after retrofitting, confirming the increased lateral stiffness of the strengthened structure.

Table 9: Maximum Storey Displacement (mm) -Existing vs. Retrofitted Structure (G+1)

Storey	Elevation (m)	Existing -X-dir (mm)	Existing -Y-dir (mm)	Retrofitted -X-dir (mm)	Retrofitted -Y-dir (mm)
1st Floor	6	0.182	0.378	0.011	0.047
Ground Floor	3	0.089	0.174	0.005	0.022
Base	0	0.000	0.000	0.000	0.000

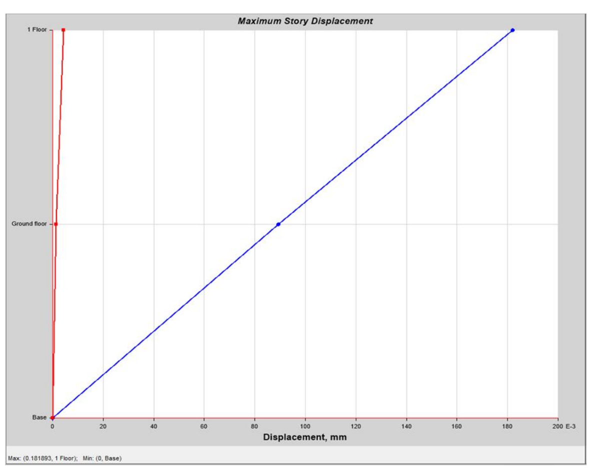

Fig. 15: Maximum Storey Displacement -Existing Structure, X-direction (G+1)

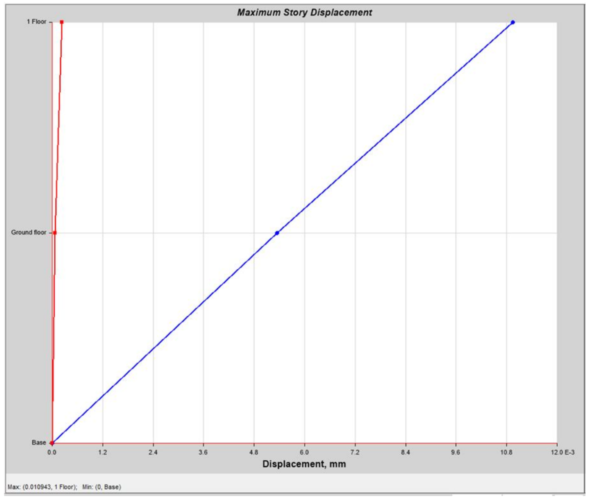

Fig. 16: Maximum Storey Displacement -Retrofitted Structure, X-direction (G+1)

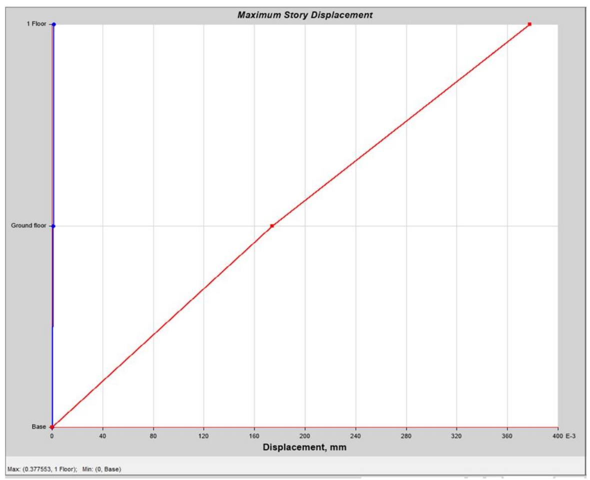

Fig. 17: Maximum Storey Displacement -Existing Structure, Y-direction (G+1)

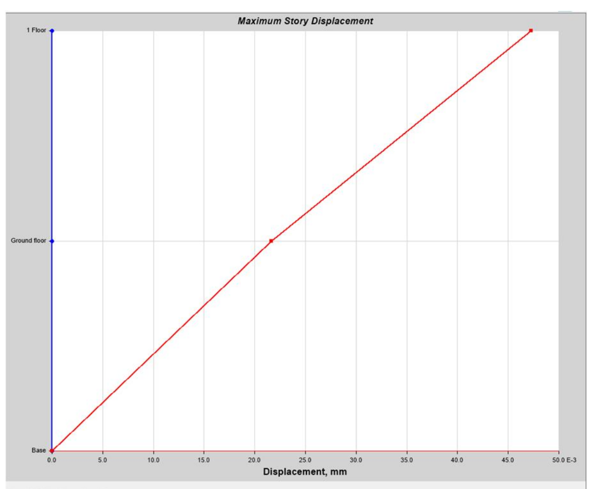

Fig. 18: Maximum Storey Displacement -Retrofitted Structure, Y-direction (G+1)

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(b) Maximum Storey Drift

Storey drift (the relative lateral displacement between two consecutive storeys divided by the storey height) is a key indicator of seismic performance and potential damage concentration. The results below show that drift values for the retrofitted structure are significantly lower than those of the existing structure in both directions.

Table 10: Maximum Storey Drift (Unitless) -Existing vs. Retrofitted Structure (G+1)

Storey	Elevation (m)	Existing -X-dir	Existing -Y-dir	Retrofitted -X-dir	Retrofitted -Y-dir
1st Floor	6	$3.1x10^{-5}$	$6.8x10^{-5}$	$2x10^{-6}$	$9x10^{-6}$
Ground Floor	3	$3.0x10^{-5}$	$5.8x10^{-5}$	$2x10^{-6}$	$7x10^{-6}$
Base	0	0	0	0	0

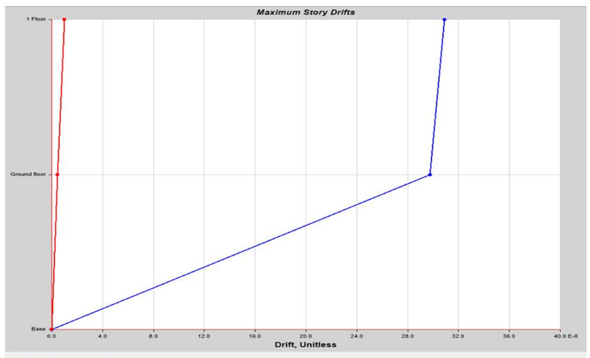

Fig. 19: Maximum Storey Drift -Existing Structure, X-direction (G+1)

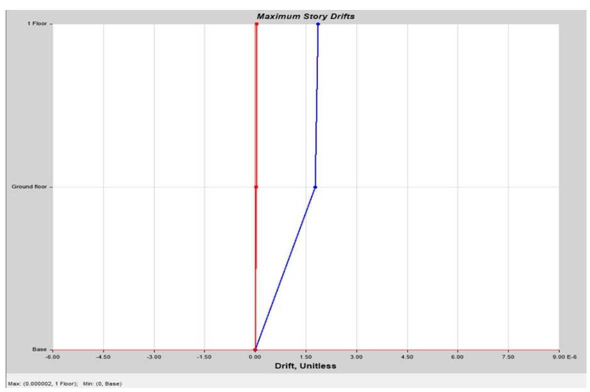

Fig. 20: Maximum Storey Drift -Retrofitted Structure, X-direction (G+1)

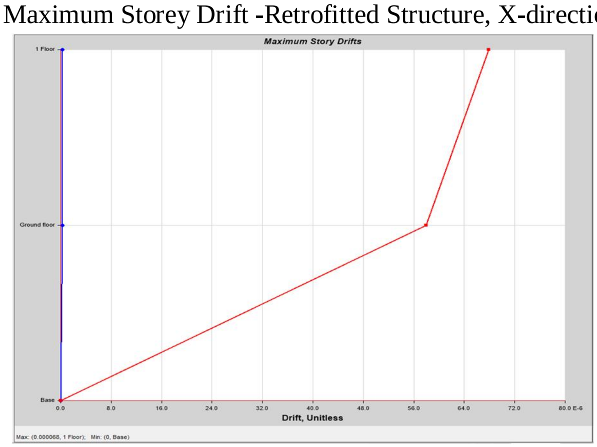

Fig. 21: Maximum Storey Drift -Existing Structure, Y-direction (G+1)

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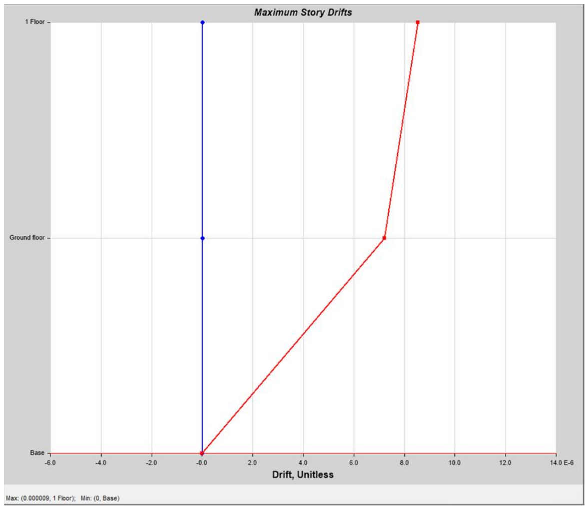

Fig. 22: Maximum Storey Drift -Retrofitted Structure, Y-direction (G+1)

(c) Storey Shear

Storey shear represents the total lateral force resisted at each level. The retrofitted structure attracts a marginally higher shear force than the existing structure, which is an expected consequence of its increased lateral stiffness drawing a greater proportion of the applied load.

Table 11: Storey Shear (kN) -Existing vs. Retrofitted Structure, X-dir = Y-dir (G+1)

Storey	Elevation (m)	Existing (kN)	Retrofitted (kN)
1st Floor	6	−401.22	−473.16
Ground Floor	3	−401.22	−473.16
Base	0	0.00	0.00

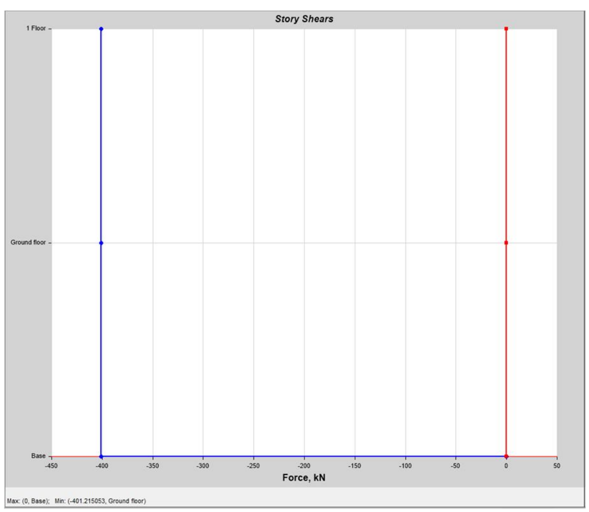

Fig. 23: Storey Shear -Existing Structure, X-direction (G+1)

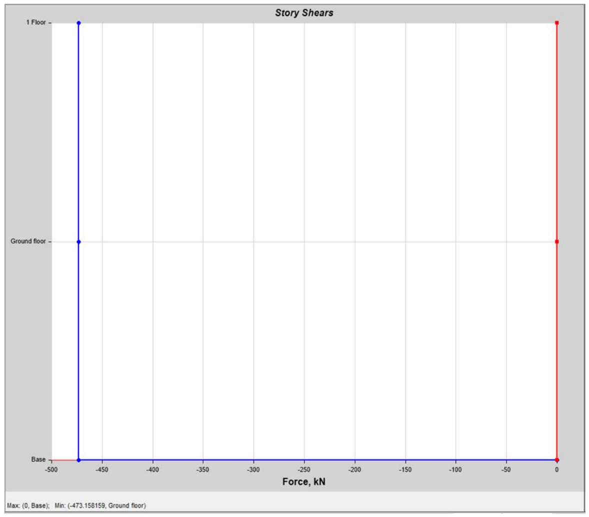

Fig. 24: Storey Shear -Retrofitted Structure, X-direction (G+1)

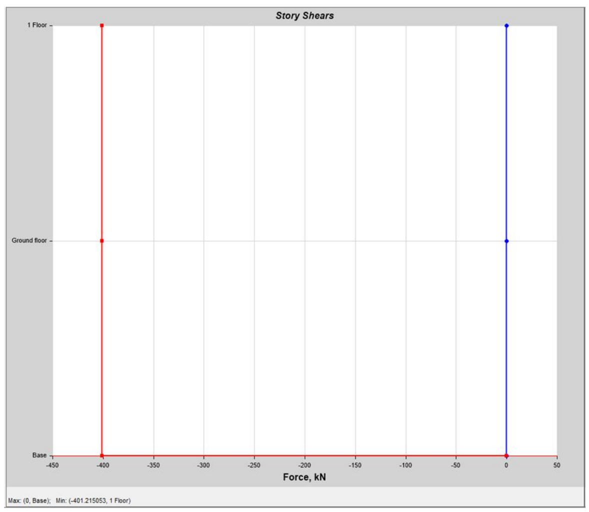

Fig. 25: Storey Shear -Existing Structure, Y-direction (G+1)

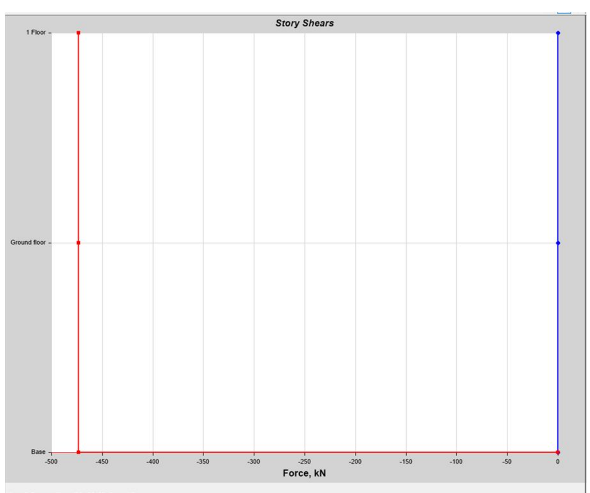

Fig. 26: Storey Shear -Retrofitted Structure, Y-direction (G+1)

(d) Storey Stiffness

Storey stiffness is the parameter most directly influenced by retrofitting. The results show a very large increase in lateral stiffness after retrofitting- approximately 19 times in the X-direction and 9 times in the Y-direction at the ground storey- which is the primary reason for the sharp reduction in displacement and drift reported above.

Table 12: Storey Stiffness (kN/m) -Existing vs. Retrofitted Structure (G+1)

Storey	Elevation (m)	Existing -X-dir (kN/m)	Existing -Y-dir (kN/m)	Retrofitted -X-dir (kN/m)	Retrofitted -Y-dir (kN/m)
1st Floor	6	4,357,333	2,004,976	85,025,921	18,522,479
Ground Floor	3	4,510,813	2,354,811	88,742,501	21,932,614
Base	0	0	0	0	0

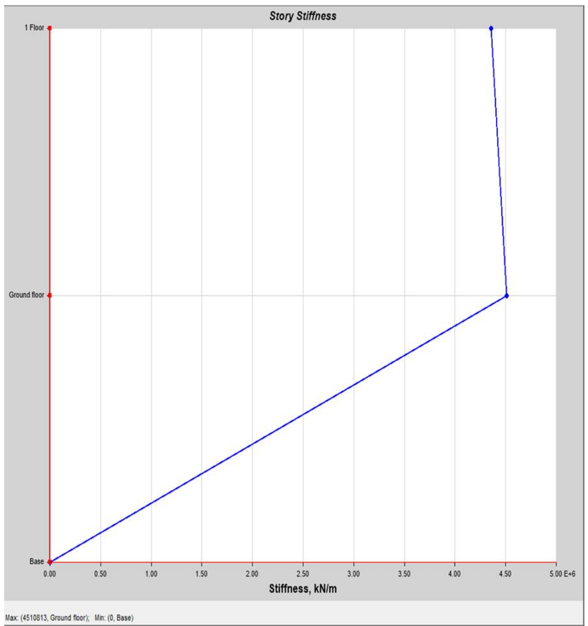

Fig. 27: Storey Stiffness -Existing Structure, X-direction (G+1)

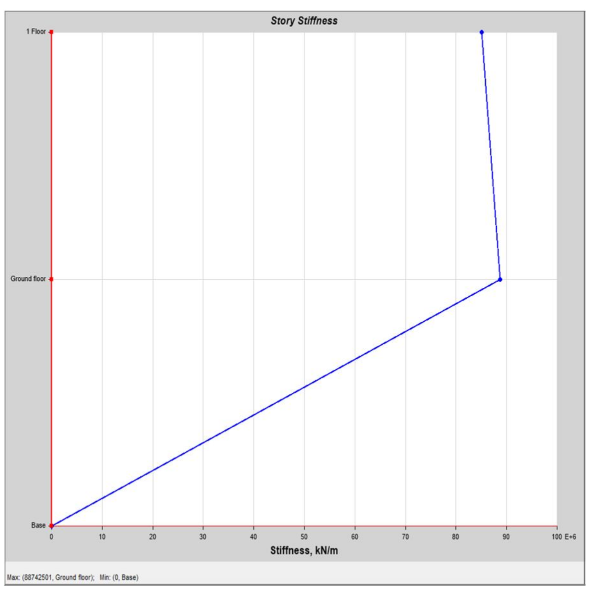

Fig. 28: Storey Stiffness -Retrofitted Structure, X-direction (G+1)

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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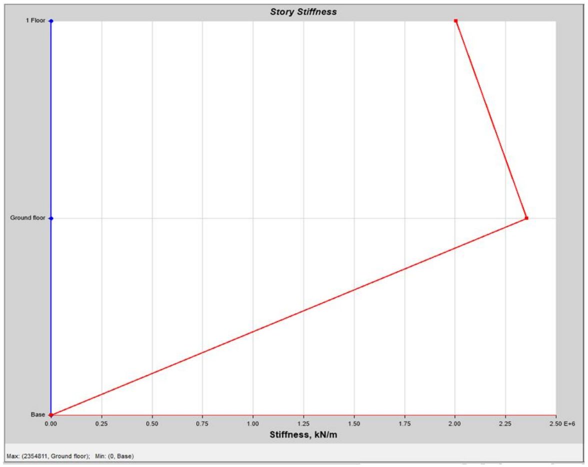

Fig. 29: Storey Stiffness -Existing Structure, Y-direction (G+1)

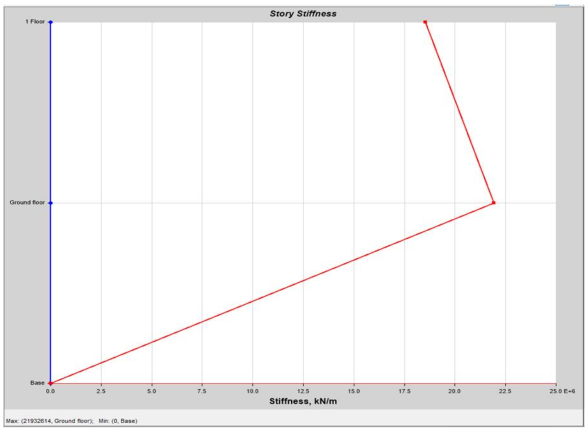

Fig. 30: Storey Stiffness -Retrofitted Structure, Y-direction (G+1)

(e) Summary of Comparative Results

Table 13: Summary -Existing vs. Retrofitted Structure at Ground Storey (G+1)

Parameter	Direction	Existing	Retrofitted	% Change
Displacement (mm)	X	0.182	0.011	↓ 94%
Displacement (mm)	Y	0.378	0.047	↓ 88%
Drift	X	$3.1x10^{-5}$	$2x10^{-6}$	↓ 94%
Drift	Y	$6.8x10^{-5}$	$9x10^{-6}$	↓ 87%
Shear (kN)	X / Y	401.22	473.16	↑ 18%
Stiffness (kN/m)	X	4,357,333	85,025,921	↑ ~19×
Stiffness (kN/m)	Y	2,004,976	18,522,479	↑ ~9×

Overall, the Case Study B results demonstrate that the retrofitting scheme substantially increases the lateral stiffness of the masonry structure, which in turn produces a marked reduction in storey displacement and storey drift in both principal directions, at the cost of a moderate increase in storey shear demand. This confirms the effectiveness of the proposed retrofit measure in improving the seismic performance of the structure.

Taken together, the two ETABS case studies provide direct structural verification of the retrofit strategies proposed in Table 3 for the RCC and unreinforced masonry typologies identified as high-risk during the Rapid Visual Screening survey: column jacketing effectively resolves member-level over-stress in RC framed buildings, while lateral stiffening substantially improves the global seismic response of masonry buildings.

V. CONCLUSIONS

Based on the data-oriented seismic vulnerability assessment of public hospitals and schools conducted using Rapid Visual Screening, together with ETABS-based structural verification of representative retrofit measures, the following conclusions are drawn:

1) A significant proportion of the surveyed public service buildings fall within moderate to high seismic vulnerability categories, indicating substantial seismic risk in the existing building stock of the Himalayan seismic zone.
2) Non-engineered masonry construction, including half-dressed stone masonry, random rubble masonry, and brick masonry, emerges as the most critical determinant of seismic vulnerability, primarily due to the absence of seismic bands, lack of vertical reinforcement, and poor construction practices.
3) Moisture-induced material degradation is identified as a major aggravating factor across all building typologies, leading to reduced material strength, accelerated crack propagation, and increased likelihood of brittle failure during seismic events.
4) Unreinforced masonry and hybrid buildings dominate the high-risk category, largely due to incremental development, stiffness discontinuities, and weak masonry-RCC interfaces, while reinforced cement concrete (RCC) buildings generally exhibit moderate vulnerability.
5) Although RCC structures demonstrate comparatively better global seismic performance, deficiencies in ductile detailing, soft-storey configurations, corrosion of reinforcement, and inadequate maintenance prevent many of them from achieving low-risk classifications.
6) The strong correlation between observed damage patterns, RVS classifications, and codal deficiencies confirms that construction typology is a more influential factor in seismic risk than building use or age alone.
7) The study confirms that Rapid Visual Screening is a reliable, scalable, and effective first-level tool for seismic vulnerability assessment and prioritization of buildings requiring detailed evaluation and retrofitting.
8) ETABS-based structural analysis of a representative G+2 RC framed structure confirms that column section jacketing (450x450 mm, M15 to 550x550 mm, M30) resolves all identified member-level deficiencies, reducing column demand/capacity ratios from a range of 1.002–1.067 (over-stressed) to 0.332–0.735 (safe), while storey drift remains within the IS 1893 permissible limit of 0.004 in both the existing and retrofitted configurations.
9) ETABS-based structural analysis of a representative G+1 masonry structure confirms that the proposed lateral stiffening retrofit substantially improves global seismic performance, reducing maximum storey displacement by 88–94% and storey drift by approximately an order of magnitude, while increasing storey stiffness by approximately 9–20 times; the corresponding 18% increase in base shear demand should be accounted for in the design of retrofit elements and their connections.
10) Code-compliant retrofitting in accordance with IS 13935 has the potential to significantly enhance life safety, structural performance, and post-earthquake functionality of existing public buildings, and the ETABS case studies presented here provide quantitative, code-referenced verification that such retrofit strategies are structurally effective.
11) Overall, the findings highlight the urgent need for systematic seismic retrofitting, improved maintenance practices, and strict enforcement of seismic design and construction codes to reduce earthquake risk in hospitals and schools located in seismically active regions.

VI. LIMITATIONS AND FUTURE WORK

Although this study provides a data-driven seismic vulnerability assessment of public hospitals and schools using Rapid Visual Screening (RVS), certain limitations should be acknowledged. The RVS assessment relies on visual inspection and observable characteristics, without detailed structural analysis, material testing, or numerical modelling for the full building inventory; therefore, the RVS results represent relative seismic risk rather than exact structural capacity for buildings that were not separately modelled. The absence of as-built drawings and construction records required inference of structural details from field observations, which may not fully capture concealed deficiencies. The study is limited to a specific Himalayan region and a finite sample of public service buildings, which may restrict broader generalization. The influence of non-structural components was assessed qualitatively, and post-retrofitting performance and cost-benefit aspects were not evaluated for the full inventory.

The ETABS structural validation presented in Section 4.3 is limited to two representative building typologies (one G+2 RC framed structure and one G+1 masonry structure) analysed using linear structural modelling; it does not extend to nonlinear pushover or time-history analysis, nor to the random rubble masonry, hybrid, and brick masonry typologies also identified in the survey. The G+1 case study did not include member-level (pier/spandrel) design check reports comparable to the column D/C ratio checks carried out for the G+2 structure.

Future work should include nonlinear seismic analysis (pushover and/or time-history) and development of fragility curves for the remaining Himalayan masonry typologies (random rubble masonry, hybrid systems), extension of ETABS-based retrofit verification to a larger and more representative sample of surveyed buildings, member-level design checks for masonry piers and spandrels in retrofitted masonry structures, long-term monitoring of retrofitted buildings, and cost-benefit analysis of large-scale retrofitting programs.

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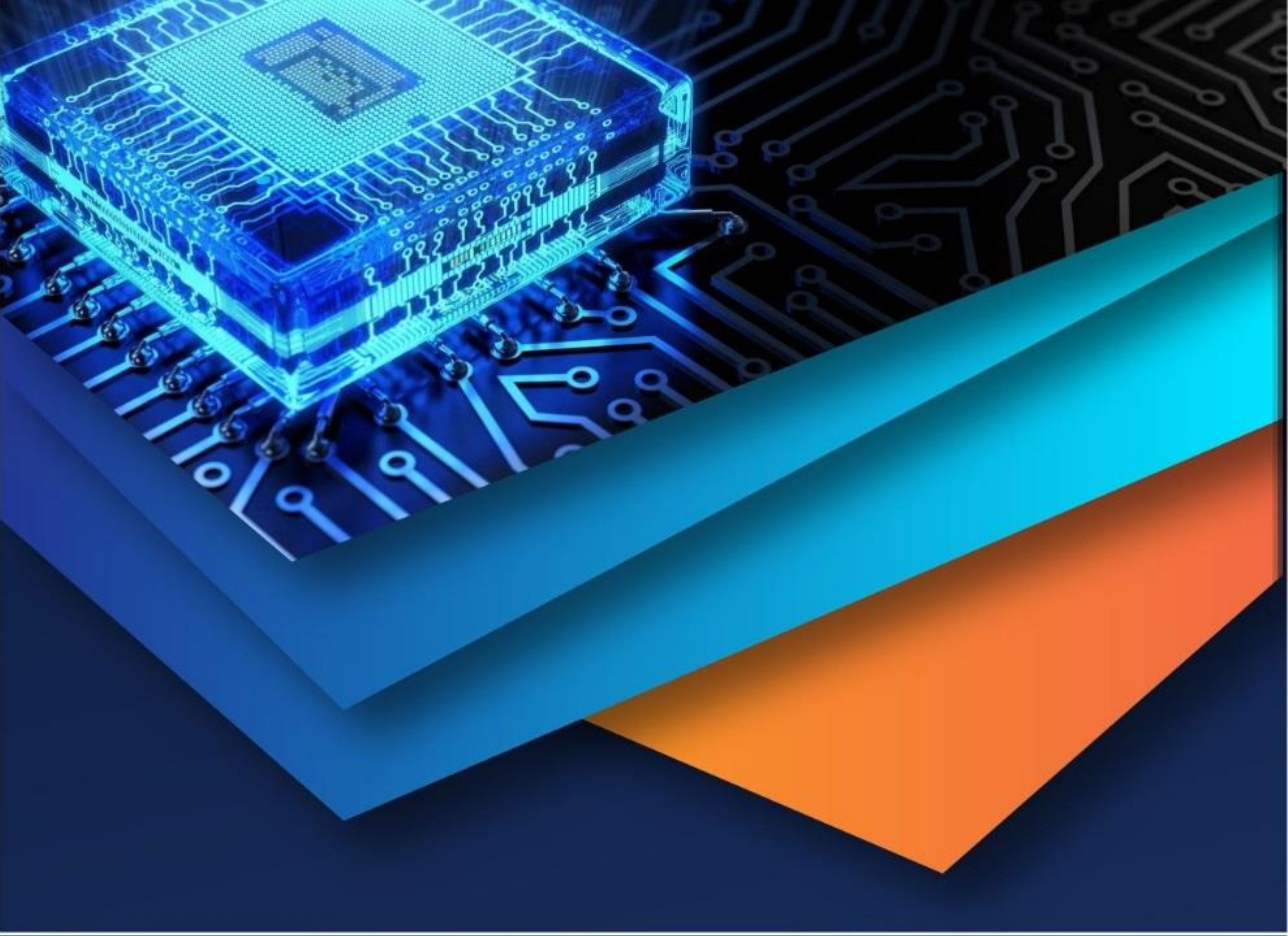

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