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Seismic Risk Evaluation and Prioritization Framework for Reinforced Concrete School Buildings

Aslam Faqeer Mohammad

maslam@cloud.neduet.edu.pk

NED University of Engineering & Technology https://orcid.org/0000-0002-2552-5466

Ameer Hamza Ali

NED University of Engineering and Technology

Muhammad Hamza Hunain

NED University of Engineering & Technology

Syed Zulqurnain Ali

NED University of Engineering and Technology

Muhmmad Hamza Javed

NED University of Engineering & Technology

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Seismic Risk Evaluation and Prioritization Framework for Reinforced Concrete School Buildings

Aslam Faqeer Mohammad*[1], Ameer Hamza Ali[1], Muhammad Hunain[1], Syed Zulqurnain Ali[1], Muhammad Hamza Javed[1]

[1] Department of Civil Engineering, NED University of Engineering and Technology, Karachi 75270, Pakistan
* Correspondence Author: maslam@cloud.neduet.edu.pk

Abstract

The structural safety of existing public-school buildings in Karachi has become a growing concern due to aging infrastructure, inadequate maintenance, and the absence of seismic design provisions in earlier construction practices. This study evaluates the seismic vulnerability of public school buildings across selected municipalities using field surveys and official records obtained from the Sindh Education and Literacy Department (SELD). A comprehensive database has been developed which includes structural characteristics, geospatial information, photographic documentation, and building condition data. Each building was assessed using the state-of-the-art FEMA P-154 Rapid Visual Screening (RVS) method, considering structural irregularities, construction typology, material degradation, and observed damage. Furthermore, to quantify seismic performance, nonlinear static analysis was performed on representative structure and converted to fragility functions, which were validated using empirical relationships from the HAZUS MH-MR4 framework. Subsequently, fragility functions were utilized to quantify the probability of damage across various limit states and to assess corresponding risk metrics, including potential economic losses, fatality rates, and anticipated downtime. The study develops risk maps based on a prioritized ranking of towns with vulnerable school buildings, allowing government authorities and stakeholders to readily identify areas requiring immediate retrofitting and to allocate resources efficiently for enhancing seismic resilience.

Keywords: Seismic vulnerability, Fragility functions, Rapid visual screening, Finite Element Modelling, School safety, Resilient infrastructure, FEMA, HAZUS, Karachi

1 Introduction

Earthquakes represent one of the most significant sources of structural damage and loss of life globally, with major events in the last two decades severely impacting human safety and national economies [1, 2]. In Pakistan, the catastrophic 2005 Kashmir earthquake became a critical turning point for policymakers and engineers, resulting in approximately 87,000 casualties, of which nearly 19,000 were school-going children [3]. The wide-scale collapse of educational institutions which is estimated at 67% of the region's schools, highlighted the extreme vulnerability of the nation's youth and the urgent need for resilient infrastructure for school buildings [3].

Karachi, Pakistan's largest megacity with a population exceeding 18 million, faces a complex seismic risk profile. Geographically, the city sits near the triple junction of the Arabian, Indian, and Asian plates and is surrounded by active tectonic structures, including the Chaman transform fault, the Kirthar fold-and-thrust belt, and the Kachchh fault system[4, 5]. Despite this high-hazard setting, often compared with Los Angeles, California; Karachi has not experienced a major damaging earthquake in its recent recorded history, leading to an "uncertain past and uncertain future" regarding its seismic potential [5].

Following the 2005 earthquake event, the government and engineering community emphasized the development and implementation of seismic codes, leading to the development of the Building Code of Pakistan (BCP)–Seismic Provisions 2007. This code was subsequently updated in a 2021 final draft. [6]. BCP classified Karachi in Seismic Zone 2B (moderate hazard) [6] meaning that while the city isn't directly on an active fault, but it's close enough to major regional faults (e.g., Makran Subduction Zone, Kirthar Fault etc) that a distant but large earthquake could still cause moderate to serious shaking, especially in poorly constructed buildings [7]. So, uncertainty lies in recurrence estimates. Regional PSHA (Probabilistic Seismic Hazard Analysis) studies, as well as more recent local studies, shows that Karachi's urban area can experience moderate ground shaking, with design spectral acceleration values of approximately 0.16g and 0.24g. This level of shaking is strong enough to damage or even endanger poorly built or weakly detailed buildings [4, 5, 7].

The structural safety of existing publicschool buildings in Karachi is a growing concern. According to the Sindh Education & Literacy Department (SELD), maintaining a conducive learning environment requires ensuring that infrastructure can withstand natural hazards to protect students and ensure the continuity of education [8]. However, much of the city's building stock consists of aging infrastructure and non-engineered construction built prior to the enforcement of the Building Code of Pakistan (BCP) 2007 [1, 3]. In case of public schools across Karachi, they are often constructed as simple reinforced-concrete (RC) frames with unreinforced or lightly reinforced masonry infill, or as load-bearing masonry buildings. Such buildings perform poorly in earthquakes [3, 9]. This study focuses on schools that are reinforced concrete (RC) frames only. Although there are load-bearing masonry buildings in Karachi, they are not considered in this study.

Performing the seismic vulnerability of a vast number of buildings for Karachi is a massive workload. The FEMA P-154 Rapid Visual Screening (RVS) methodology offers a cost-effective "sidewalk survey" tool to identify, record, and rank buildings that are potentially hazardous without the high cost of immediate detailed analysis for every structure. By evaluating structural irregularities, construction typology, and material degradation such as corrosion and cracks, RVS provides the easiness to divide the buildings into those with acceptable performance and those requiring urgent detailed structural assessment [10].

To bridge the gap between qualitative screening and quantitative risk assessment, researchers use analytical fragility functions to estimate the probability of damage at different limit states, such as Immediate Occupancy, Life-Safety and Collapse Prevention [1]. The fragility functions can be made in two ways, either by Non Linear Static Analysis (NLSA) such as pushover analysis guided By FEMA 306 [11] which are known as Analytical fragility functions or by using the HAZUS MH-MR4 framework, which are known as Empirical fragility functions [12]. By integrating these fragility functions with city-level seismic hazard data obtained from SELD portal [13], one can estimate the associated risks such as potential economic losses and fatality ratios [9] for the publicschool buildings in Karachi.

This research aims to develop a Seismic Risk Evaluation and Prioritization Framework specifically for public school buildings across the town municipalities of Karachi. By utilizing official records from the Annual School Census (ASC) [8], extracting the data from SELD portal [13] and conducting field assessments, this study establishes a comprehensive framework to visualize seismic risk patterns in Karachi through spatial mapping. The final framework provides a prioritized ranking of towns, enabling government stakeholders to efficiently distribute limited resources towards immediate retrofitting and safety considerations, ultimately ensuring a safer environment for the students and staff of government schools in Karachi.

2 Research Significance and Methodology

Disasters affect all types of built environments, but school infrastructure is particularly critical due to the extreme vulnerability of its occupants [9]. Karachi, a megacity with a population exceeding **18 million**, faces a high level of seismic hazard due to its complex tectonic setting. Although the Karachi region has not experienced a major earthquake in recent history, this absence does not eliminate the potential risk of future seismic events [4, 5]. The uncertainty was present and it is still present and thus research is necessary that if a seismic event occurs then what will be its effects on the people, and especially, what will be its effects on the school infrastructure of Karachi.

This research is significant as it addresses a critical gap in disaster risk reduction by developing a standardized framework to evaluate the structural vulnerability of aging and neglected school buildings in Karachi. By establishing a prioritized ranking of towns, the study provides the Sindh Education and Literacy Department (SELD) and other stakeholders a basis for decisions which is data-driven, for the efficient allocation of limited resources toward retrofitting and safety interventions [8, 9].

The proposed seismic risk assessment framework that has been utilized in this study is represented in Figure 1.

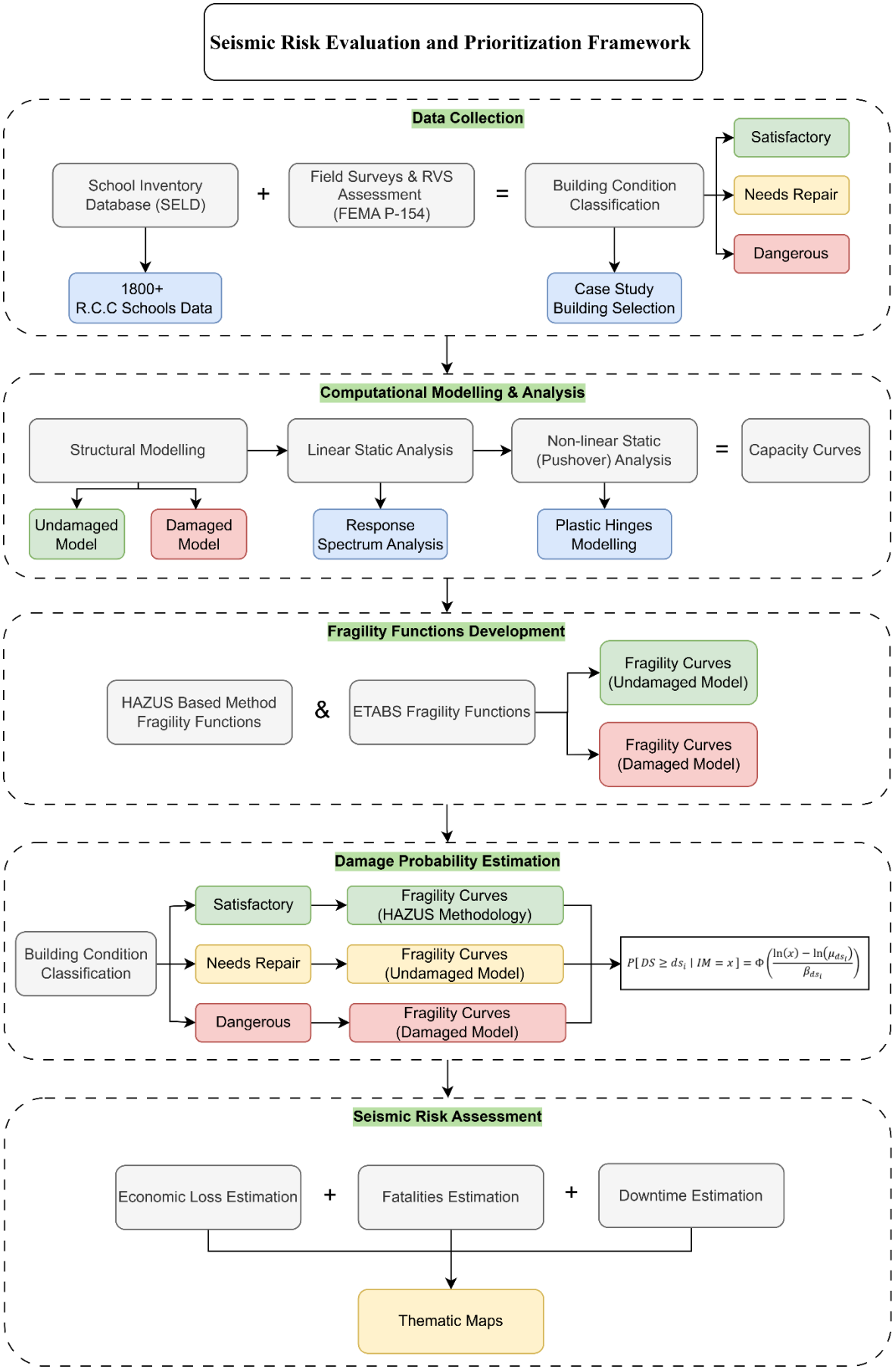


Figure 1 - Seismic Risk Assessment and Prioritization Framework

3 Data Collection

3.1 Study Area for Survey Coverage

As per the revised administration planning of Karachi by Sindh Government in 2024, Karachi is divided into seven districts and twenty-five towns, which serve as the primary urban governance units. These districts include South District, East District, West District, Central District, Korangi District, Malir District, and Keamari District. Each district consists of several towns that further divide the urban area into smaller administrative zones as shown in the Figure 2 developed by Urban Resource Center [14, 15].

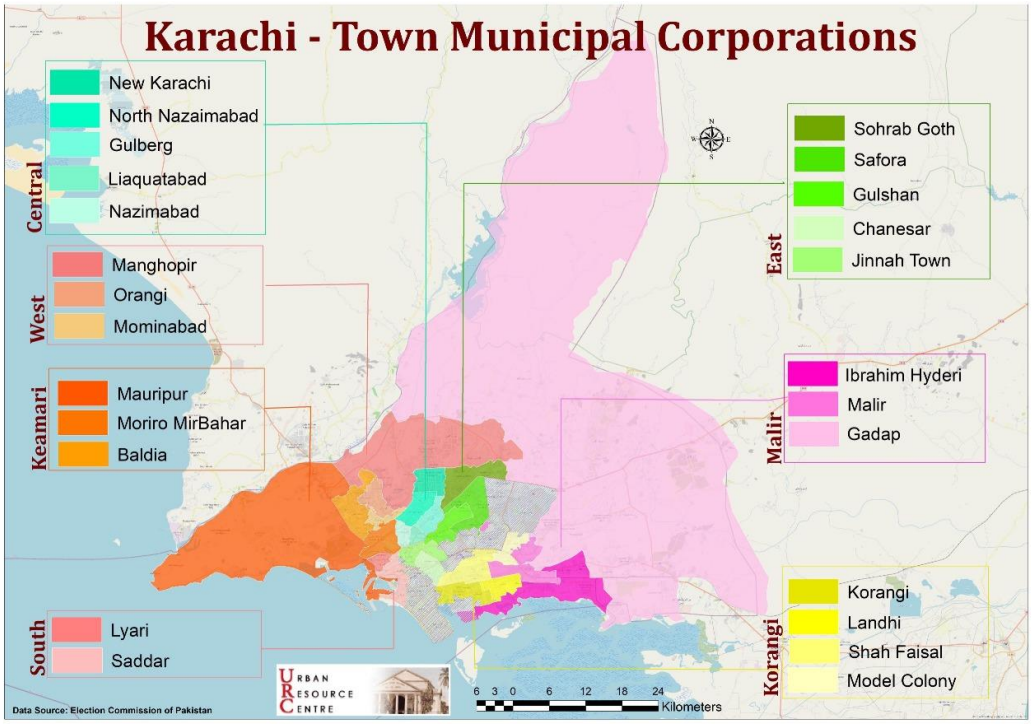


Figure 2 - Administrative Map of Karachi

For this study, ten public school buildings were selected from each town of Karachi, resulting in 250 schools in total which represents different geographic locations, construction periods, and structural typologies across the city.

3.2 Characteristics of Public-School Buildings

Most public-school buildings in Karachi consist of reinforced concrete frame structures with masonry infill walls or load-bearing masonry construction. Many of these buildings were constructed before the implementation of modern seismic codes (BCP-2007 [16] and BCP-2021 [6]) and often show signs of deterioration, inadequate maintenance, and structural deficiencies. The selected schools include mix type of schools like primary, middle, secondary, and higher secondary etc. obtained from the Sindh Education and Literacy Department (SELD) database and verified through field surveys [13].

3.3 Data Collection from SELD Portal

The primary data regarding the inventory of public school buildings was retrieved from the official records of the Sindh Education and Literacy Department (SELD) [13] and its Reform Support Unit

(RSU)[17]. This study specifically utilized the 32nd Annual School Census (ASC) 2023-2024, which provides a comprehensive overview of school infrastructure, enrolments, and faculty statistics [8]. The Sindh Education and Literacy Department (SELD) database contains the data for 1806 RC moment frame schools which are used later in the study for seismic vulnerability assessment. Furthermore, in order to verify the data from available database and to perform the Rapid Visual Screening [10], ten random public school buildings were selected from each town of Karachi for field survey, resulting in 250 schools in total to validate the data in the portal.

These school records include essential parameters for seismic risk evaluation, such as the number of classrooms, building ownership (government-owned, shared, or rented), and the physical condition of the building categorized as **satisfactory, need repair, or dangerous.** The information that can be obtained about the schools from the SELD portal [13] is shown in Figure 3.

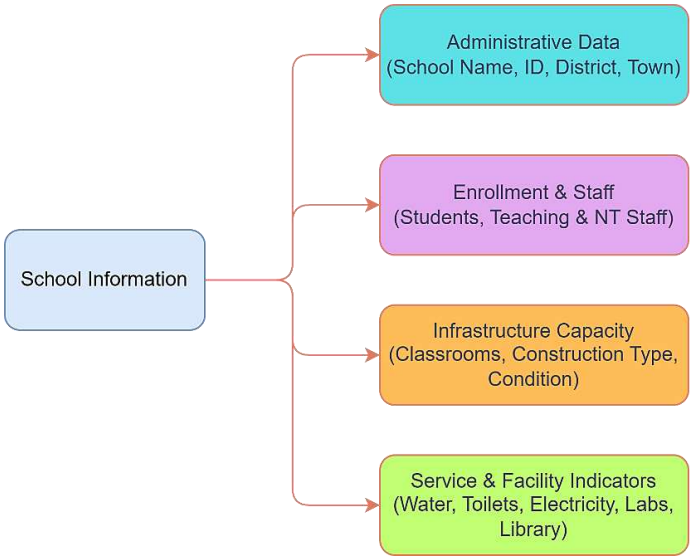


Figure 3 - Different categories of school information extracted from the database.

The data was extracted from the portal [13] for all the schools of Karachi. Then the data was cleaned manually and only the schools which have school type as Pakka/ RC were considered. The information that can be extracted from the portal is shown in Table 1 for a particular school.

Table 1: An example of the extracted data for a particular school.

Administrative Data	School Name	GBPS: AL NOOR SOCIETY NO 3 (408140029)
	Institution ID	408140029
	District	Karachi Central
	Town	Gulberg Town
Enrolment & Staff	Enrolments	Total:137
	Teaching Staff	T:12
	Non-Teaching Staff	NT:1
Infrastructure Capacity	No of classrooms	Total:13
	Type of construction	Pakka/RCC
	Existing Condition	Needs Repair
Service Indicators	Drinking Water	✔
	Toilets	✔
	Electricity	✔
	Science Lab	✘
	Computer Lab	✘
	Library	✘

3.4 Data Collection from Field Surveys

The field visits to the selected public-school buildings across different towns of Karachi provided a realistic picture of their present structural and functional conditions. During the survey, both structural and non-structural aspects were noted. Non-structural deficiencies include broken or inadequate doors and windows, roof leakage, plaster damage etc. Since this study will utilize the structural parameters so these were visually inspected as per FEMA P-154 [10], and photographs were taken to document the condition of each school. The observations were later grouped into common categories of defects and deterioration patterns that are summarized below in Figure 4.

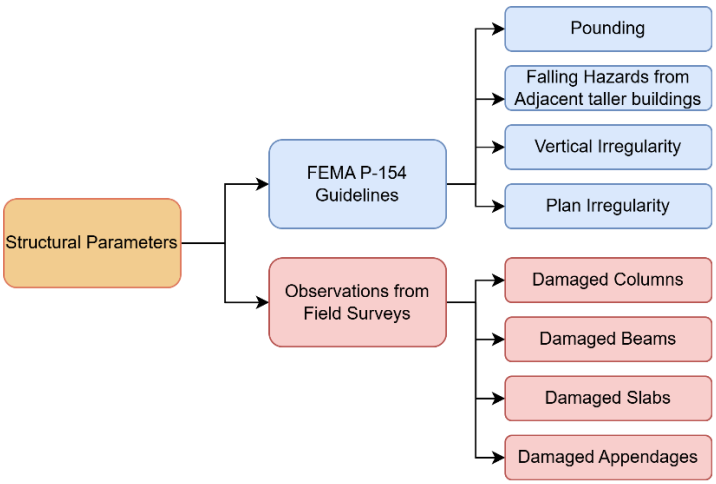


Figure 4 - Structural Parameters obtained from Field Surveys

The observed damages in the different structural members recorded from field surveys are shown in Figure 5 to Figure 8



Figure 5 - a) damage beam-column joint, b) cracking in column, c) exposed corroded reinforcement in column

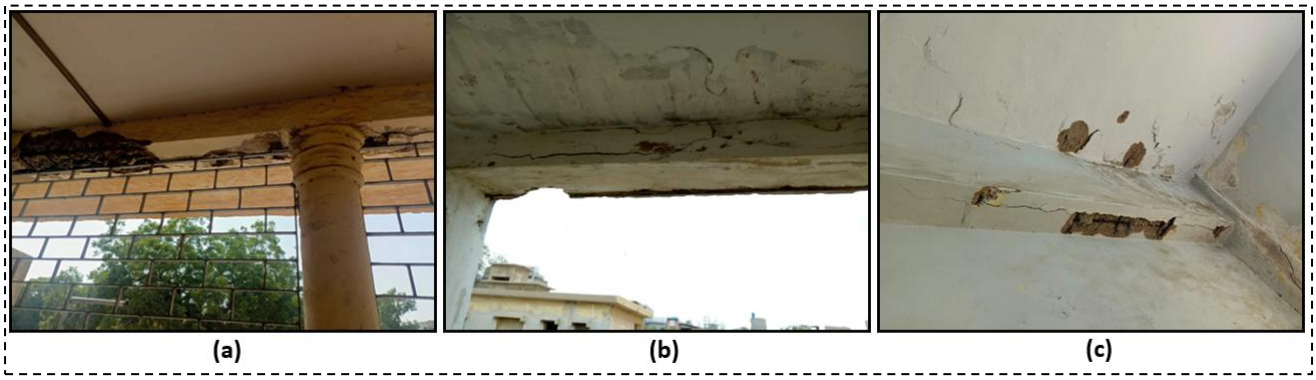


Figure 6 - a) exposed rebars in beams, b) extensive cracking in beams, c) spalled concrete in beams



Figure 7 - a) surface delamination of slab, b) exposed reinforcement with cracking in slab, c) severe spalling and concrete cover loss in slab.

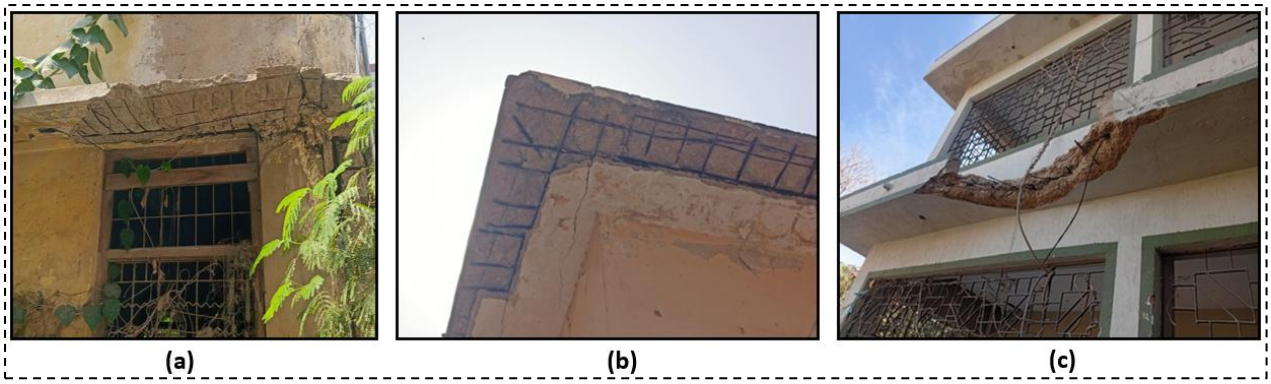


Figure 8 - a) exposed reinforcement at appendage edge, b) cracking and cover loss in appendages, c) severe damage with exposed hanging rebars in appendage.

3.5 Selection of Case Study School Structure

As aforementioned, the ASC divides schools into three main categories as **"Satisfactory", "Needs Repair"** and **"Dangerous"** [8].

A representative government school building was selected from the surveyed dataset to conduct nonlinear structural analysis and to develop analytical fragility functions. The selected structure is **GGHSS Secondary School (SEMIS ID: 408080108)** located in Gulshan Town, Karachi. The school was identified from the database of the Sindh Education and Literacy Department (SELD) [13] and was classified as **"Dangerous"** based on the official records and also verified by field survey.

The school accommodates a large number of occupants as compared to other available schools in database, which includes 768 female students**,** 18 teaching staff**,** and 6 non-teaching staff**,** highlighting the significant life-safety considerations associated with potential structural failure during seismic events [13].

Field surveys revealed severe structural deterioration in several structural components of the building. The major observed deficiencies included: 1) cracked and partially collapse reinforced concrete slab, 2) exposed and corroded reinforcement bars, 3) diagonal shear cracks in beams, and 4) concrete spalling in columns.



Figure 9 - a) status of classroom, b) damage in different RC components

These conditions (Figure 9) indicate significant structural issues and potential reduction in load-carrying capacity of the structural system. Such deficiencies are typical of aging reinforced concrete buildings constructed without modern seismic detailing, subjected to long-term environmental exposure and lack of maintenance [11].

4 Computational Modelling

The structural model of the case study school structure was developed in ETABS [18] on the basis of the prepared as-built structural drawings from field surveys. The objective of the computational modelling was to realistically represent the structural behaviour of the selected reinforced concrete (RC) school building under gravity and seismic loading conditions and to provide the basis for nonlinear performance assessment for both damaged and undamaged structure state for the fragility function development.

4.1 Structural Configuration of Selected Building

The structural configuration of the selected school building consists of a single-storey reinforced concrete frame structure with base to plinth height of 6 ft (1800mm) and plinth to roof height of 12 ft (3600mm) and an L-shaped plan geometry as shown in Figure 10 and Figure 11. The L-shaped plan configuration was frequently observed during the field surveys and is also consistent with typical school building typologies reported in previous vulnerability studies of Pakistani educational infrastructure conducted by Zain et al. [3]. Therefore, this building was representative of the typical building typology present in the case-study region.

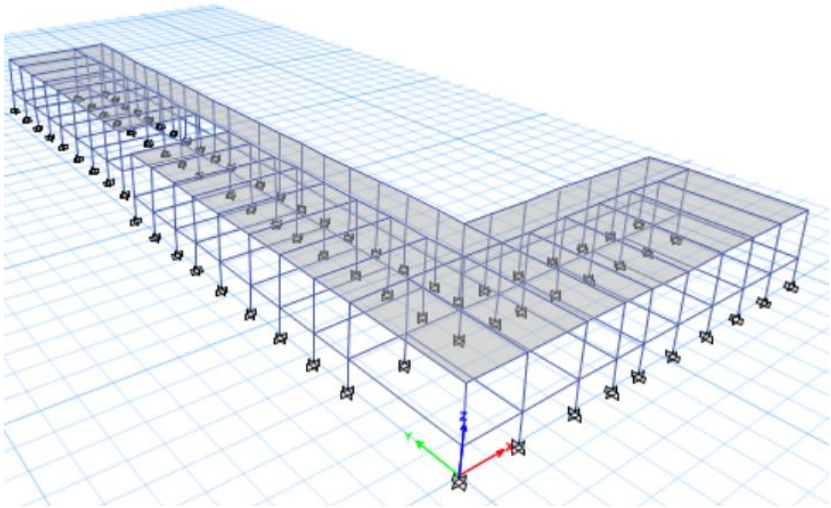


Figure 10 - 3D finite element model (Front View or North-east view)

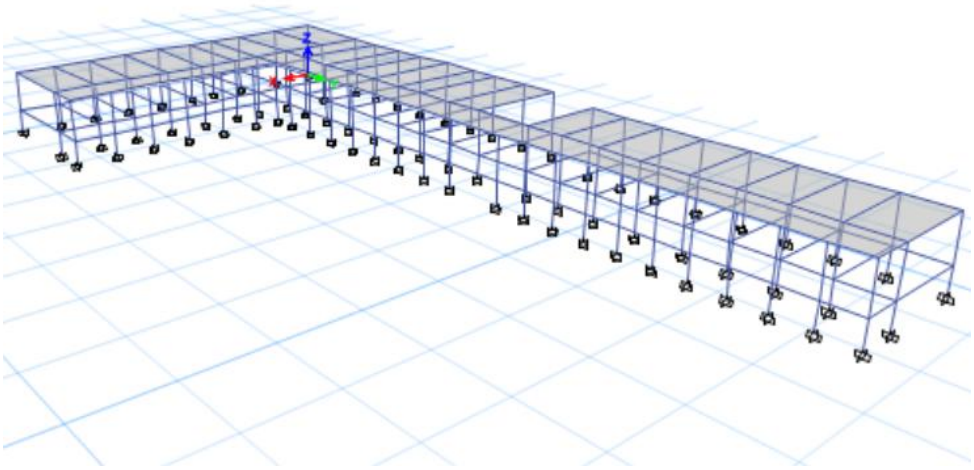


Figure 11 - 3D finite element model (Backside view or South-west view)

The structure has typical bay and member sizes as these are common in public school buildings. Members sizes that were noted for structure are shown in Table 2

Table 2: Structural Member Dimensions of the Case Study School Building

Structural Element	Member ID	Dimensions	Location / Description
Column	C1	12 in (300mm) × 12 in (300mm)	Exterior columns
Column	C2	10 in (250 mm) × 24 in (600 mm)	Interior columns
Column	C3	10 in (250 mm) × 30 in (750 mm)	Major internal load-bearing columns
Beams	B1	8 in × 36 in	Beams
Slabs	—	Thickness = 6 in	Reinforced concrete floor slab

Material properties were assigned based on available information and field observations. Due to unavailability of non-destructive testing method, the compressive strength of concrete was taken as f'c = 2 ksi, as recommended for older reinforced concrete structures in ASCE 41 [19]. The yield strength of reinforcing steel was taken as fy = 60 ksi which corresponds to the typical strength of deformed reinforcing bars observed during site inspection. These material values reflect typical construction practices for older school buildings in Karachi and are consistent with previous studies on seismic vulnerability of school buildings in Pakistan [3].

The summary of material properties and gravity load values adopted for the structural modelling are given in Table 3. These parameters were defined in the analytical model to represent the typical construction characteristics and loading conditions of the selected school building.

Table 3: Material Properties and Loading Values Used for Structural Modelling

Materials Characteristics	Strength (ksi)	Load Type	Value
Concrete compressive strength (f'c)	2	Live Load	24 (psf)
Reinforcing steel yield strength (fy)	60	Infill Partitioning Load	0.675 (k/ft)

4.2 Linear Static Analysis

Initially, a linear structural analysis was performed to evaluate the basic structural response characteristics of the building under gravity and seismic loading. Modal analysis and response spectrum analysis were conducted to determine important structural parameters such as the fundamental period (Table 4), modal mass participation (Table 5), base shear and inter-storey drift (Table 6). These results were checked according to ASCE 7-16 [20] and UBC 97 [21] and are shown in . These results provided an initial understanding of the global stiffness and dynamic behaviour of the building and also served as a verification step for the developed computational model.

Table 4: Modal Periods and Frequencies

Mode	Period (sec)	Frequency (cyc/sec)	Dominant Direction
1	0.269	3.719	UX / UY
2	0.219	4.558	UX / UY
3	0.195	5.123	UY
4	0.06	16.659	UX / RZ
5	0.055	18.18	UX
6	0.048	20.654	UY

Table 5: Cumulative Modal Participating Mass Ratios

Mode	Cumulative UX (%)	Cumulative UY (%)
1	35.09	2.38
2	69.67	14.79
3	72.05	71.56
4	75.59	74.26
5	99.86	75.26
6	99.99	99.99

Table 6: Summary of Base Reaction and Inter-story Drift Results

Load Case	Direction	Max Inter-story Drift (Story1)	Allowable Drift (UBC 97)	Status	Total Base Shear (kips)
Seismic	X	0.001163	0.0025 (1/400)	Acceptable	528.9
Seismic	Y	0.00067	0.0025 (1/400)	Acceptable	528.9

For seismic response evaluation, a response spectrum function was defined in ETABS [18] using the provisions of UBC 97. The UBC97 spectrum was used for the principal structural analyses because the Building Code of Pakistan (BCP 2007) seismic provisions are primarily derived from UBC97 methodology and remain widely used in engineering practice within Pakistan. Since Karachi is classified within Seismic Zone 2B [16], therefore the spectral coefficients C_a = 0.28 and C_v = 0.4, and Importance factor = 1.25 for school buildings [21], assuming site class D for overall Karachi. These

parameters were used to develop the response spectrum curve within the software environment as shown in Figure 12.

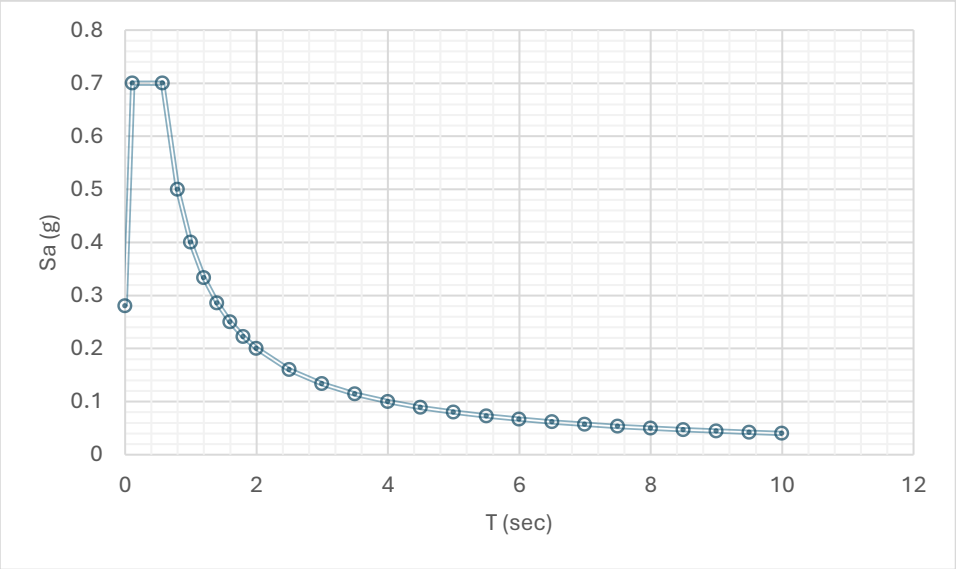


Figure 12 - Response Spectrum for Karachi (UBC 97)

4.3 Nonlinear Static (Pushover) Analysis

To evaluate the seismic performance of the case study school building beyond the elastic range, a nonlinear static (pushover) analysis was performed using ETABS [18]. Pushover analysis is a widely adopted performance-based seismic assessment technique that enables the evaluation of structural capacity by incrementally applying lateral loads to the structure until significant nonlinear behavior develops. This procedure allows engineers to estimate the progressive formation of plastic hinges and identify potential failure mechanisms in structural systems. [22, 23].

The most common two methods of simulating nonlinear behaviour of building are fiber plasticity modelling and lumped plasticity modelling [24]. Both approaches are widely used in performance-based seismic assessment, but they differ in the representation of material nonlinearity and computational effort. Fiber plasticity, also known as distributed plasticity modeling, represents the cross-section of a structural member by discretizing it into multiple fibers consisting of concrete and reinforcing steel materials. Nonlinearity develops gradually along the member length through stress–strain relationships of individual fibers. In the lumped plasticity approach, nonlinear behaviour is assumed to be concentrated at discrete locations within structural members, typically at beam-column ends where plastic hinges are expected to form during seismic loading. The remaining portion of the member is assumed to remain linearly elastic. The nonlinear response is represented using idealized force–deformation hinge properties [22, 24, 25].

In this study, the lumped plasticity modelling approach [24] was adopted to simulate the nonlinear behaviour of structural members because it is a computationally efficient and practically suitable method for the seismic assessment framework developed in this study. Plastic hinges were assigned at critical locations of beams and columns to represent the potential inelastic deformation that may occur during strong ground motion as defined by FEMA 306 [11]. The pushover analysis was carried out for two states of structures: Undamaged and Damaged. By applying monotonically increasing lateral loads to the structural model in the principal X and Y directions of the building and as the applied lateral

load increased, plastic hinges gradually formed in structural members, allowing the simulation of progressive structural damage and redistribution of internal forces. This procedure provides an estimate of the structural capacity and deformation demand under seismic loading conditions [23].

Since the current research objective is to develop the fragility functions from the pushover analysis results, so, the pushover analysis was performed on same structure for two different conditions: 1) undamaged and 2) damaged state. As described by Bilgin [24], under seismic loading, beams generally form plastic hinges near their ends, which are modelled using M3 hinges (moment about the major axis). Columns, however, demand more sophisticated representation because of the interaction between axial forces and bending moments. This requires P-M2-M3 hinges, which capture the coupling between axial load and biaxial flexural behaviour. Therefore, in developed FE model, the M3 flexure hinges were assigned on beams and Axial P, M2, M3 hinges (three hinges at same place) were assigned on columns as explained in literature [25]. Since herein lumped plasticity modelling approach has been adopted [24], non-linear behaviour of hinges depends on the backbone curve as shown in Figure 13.

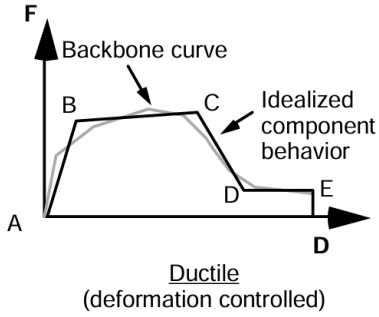


Figure 13 - Idealised force-deformation relationship for nonlinear hinge modelling (FEMA 306)

As reported in the database available and verified through field surveys, there are several types of damage found in case-study structure, so in order to model the hinges for damaged and undamaged state, FEMA 306 "Component Modelling Criteria" [11] as shown in Figure 14 was adopted for modifying the default backbone curve.

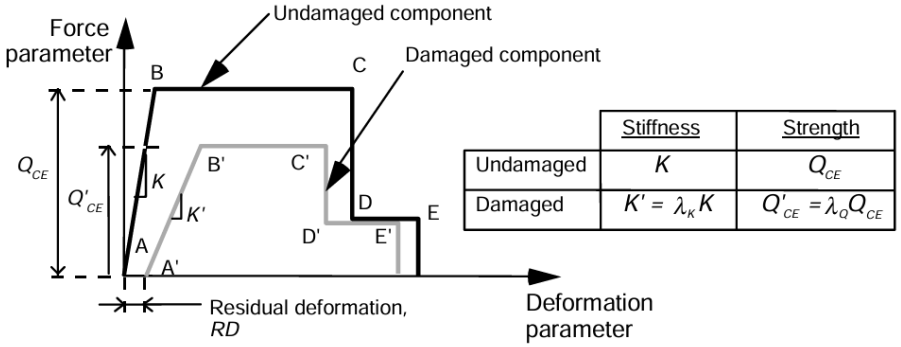


Figure 14 - Component Modelling Criteria (FEMA 306) for damage and undamaged state

FEMA 306 [11] define the factors which can be used to modify component properties and can be used to model the existing damage in the structural modelling. These factors as defined by FEMA 306 [11] are as follows:

- λK = modification factor for idealized component force-deformation curve accounting for change in effective initial stiffness resulting from earthquake damage.
- λQ = modification factor for idealized component force-deformation curve accounting for Deformation parameter change in expected strength resulting from earthquake damage.
- λD = modification factor applied to component deformation acceptability limits accounting for earthquake damage.

These factors are given in FEMA 306 [11] described by the severity and visual description of damages. For current case-study structure case, also by using recorded damages in Figure 5 and Figure 6, these two criteria were adopted for modelling the damages in the structure as shown in Figure 15 and Figure 16 by modifying the hinges properties for columns and beams, respectively.

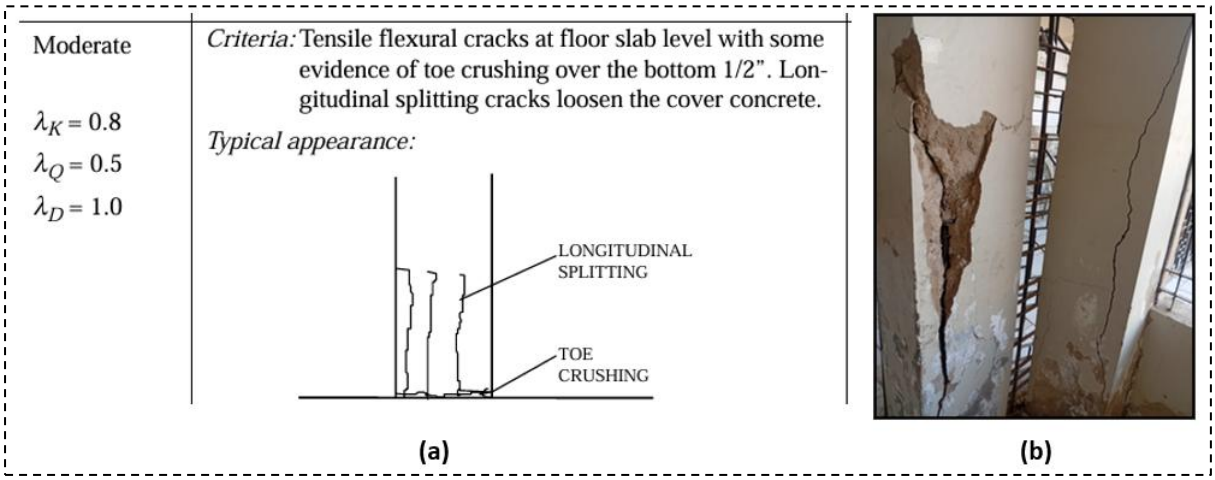


Figure 15 - a) Component Modification Factors adapted for columns (FEMA 306), b) Condition of column recorded from field

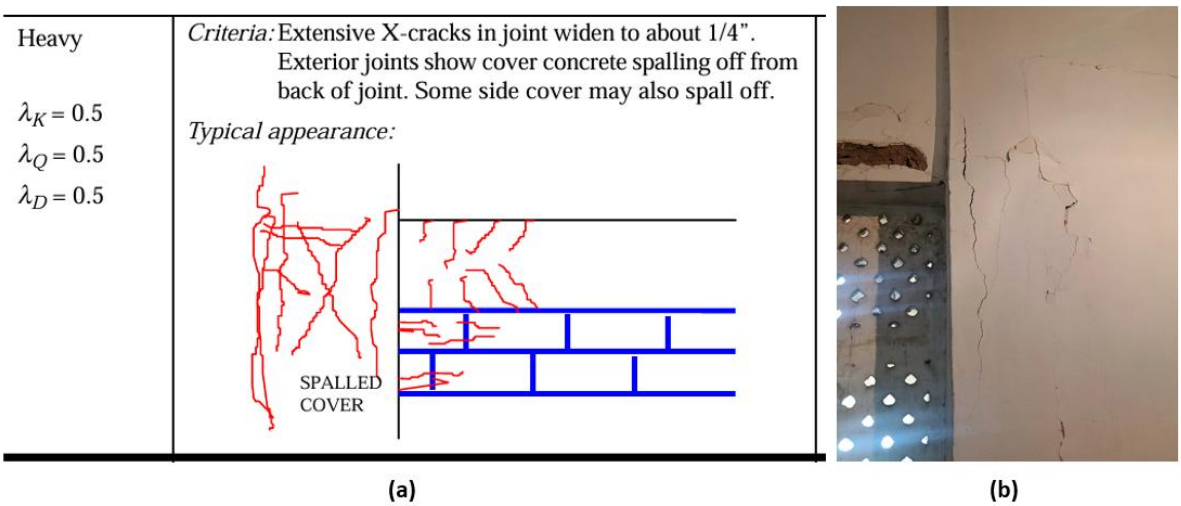


Figure 16 - a) Component Modification Factors adapted for beams (FEMA 306), b) Condition of beam recorded from field

For the modelling of structure in undamaged state, no modification factors were applied in M3 hinge for beams and Axial P, M2, M3 hinges for columns and pushover analysis was carried out using conventional approach. However, for modelling of structure in damaged state, λQ factor was applied

at backbone curve of M3 hinge for beams and Axial P, M2, M3 [26] for columns. Although, one can use the Axial P-hinge and apply the λQ factor to it. For applying the λK factor, it was directly applied as stiffness property modifier in both beams and columns.

The results of the pushover analysis were represented through a capacity curve, which relates the base shear to the roof displacement of the structure. The capacity curve obtained from both the damaged and undamaged structural state is shown in Figure 17.

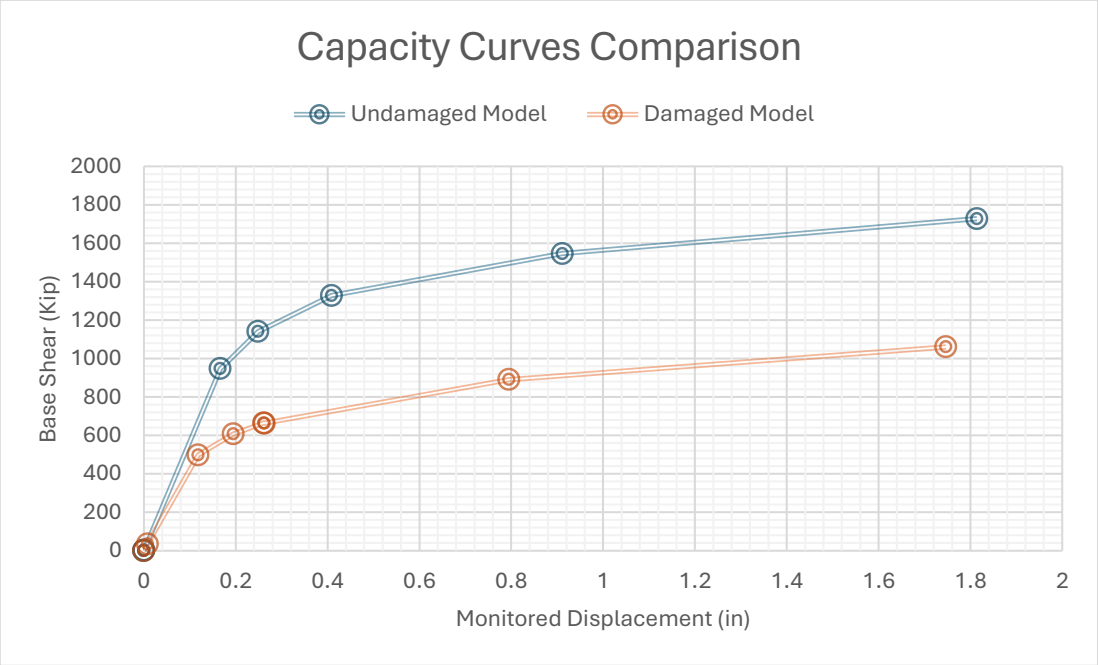


Figure 17 - Comparison of Capacity Curves for Damaged and Undamaged state of structure.

Figure 17 illustrates the changes in the capacity curves from undamaged state to damaged state of structure occurred due to the change of the structural response because of the modification factors.

Since capacity curves obtained from pushover analysis are commonly used to evaluate structural performance levels and to develop fragility relationships for seismic vulnerability assessment as research conducted in [22] and by [27]. The use of nonlinear static pushover analysis is considered as appropriate for this study because the primary objective was to develop representative fragility functions for a large inventory of school buildings across Karachi [13, 17], therefore the obtained capacity curves in **Error! Reference source not found.** will be used later in the study.

5 Development of Fragility Functions

Fragility functions are mathematical relationships that express the conditional probability that a structural system or component will reach or exceed a specific limit state (such as Slight, Moderate, Extensive, or Complete damage) as a function of a measure of environmental excitation, typically ground motion intensity [28]. Alternatively, a fragility function represents the **cumulative distribution function (CDF)** of the capacity of an asset to resist a defined undesirable limit state, measured in terms of the excitation level at which that limit state is exceeded.

Mathematically, it is given as:

$$P[\,DS \geq ds_i \mid IM = x\,] = \Phi\left(\frac{\ln(x) - \ln(\mu_{ds_i})}{\beta_{ds_i}}\right) \tag{5.1}$$

where,

- $P[\,DS \geq ds_i \mid IM = x\,]$
  Probability that damage state ds_i is exceeded.
- IM = Intensity Measure (PGA, spectral acceleration, spectral displacement, etc.)
- x = Specific value of intensity
- μ_{ds_i}= Median intensity at which damage state ds_i is reached
- β_{ds_i}= Logarithmic standard deviation (dispersion)
- Φ = Standard normal cumulative distribution function

For this study, three types of fragility functions were developed in terms of PGA. These consist of one empirical fragility function from HAZUS [12] and two analytical fragility functions from ETABS pushover results [3]..

Defining objective, measurable, and testable limit states is critical for ensuring the fragility functions pass the "clarity test" and remain consistent across different observers [28]. As used by many researches like [3, 28], this framework utilizes the four structural damage states defined by the HAZUS MH-MR4 framework: **Slight, Moderate, Extensive, and Complete** as shown in Figure 18.

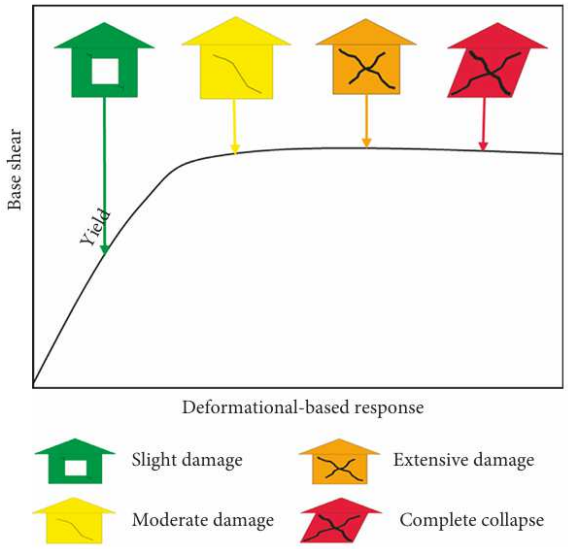


Figure 18 Damage states defined by HAZUS.

5.1 Fragility Functions from HAZUS

The fragility functions from HAZUS [12] were developed as the benchmark curves and to compare the fragility curves obtained from ETABS [18]. HAZUS provides standardized fragility relationships for different building typologies based on empirical observations and analytical studies [12]. For this study,

Chapter 6 of HAZUS was referred because as per Table 6.1 from HAZUS, it classifies school as essential facility with label as "EFS1" for "Primary/ Secondary Schools" [12].

Since we will be developing fragility functions in terms of PGA so section 6.4.4 which refers to "Structural Fragility Curves - Equivalent Peak Ground Acceleration" of HAZUS is used. Based on the structural characteristics observed during field surveys, the government school buildings in Karachi were identified as reinforced concrete moment-resisting frame structures with low-rise configurations. According to the building classification system provided in the HAZUS , such structures fall under the **C1L category** [12], which represents low-rise reinforced concrete moment frame buildings with low-code seismic design level. These buildings typically consist of reinforced concrete frames supporting slab systems with masonry infill walls, and they generally range from one to three storeys in height.

Using Table-6.7c from [12], the values for beta and median were adapted for the development of fragility functions are shown in Table 7

Table 7: Values for median and beta for damage states (HAZUS)

Damage State	μ_i (Median)	β_i (lognormal dispersion)
Slight	0.17	0.64
Moderate	0.25	0.64
Extensive	0.39	0.64
Complete	0.65	0.64

These values were substituted in Eq-(5.1) and following fragility curves were developed shown in Figure 19.

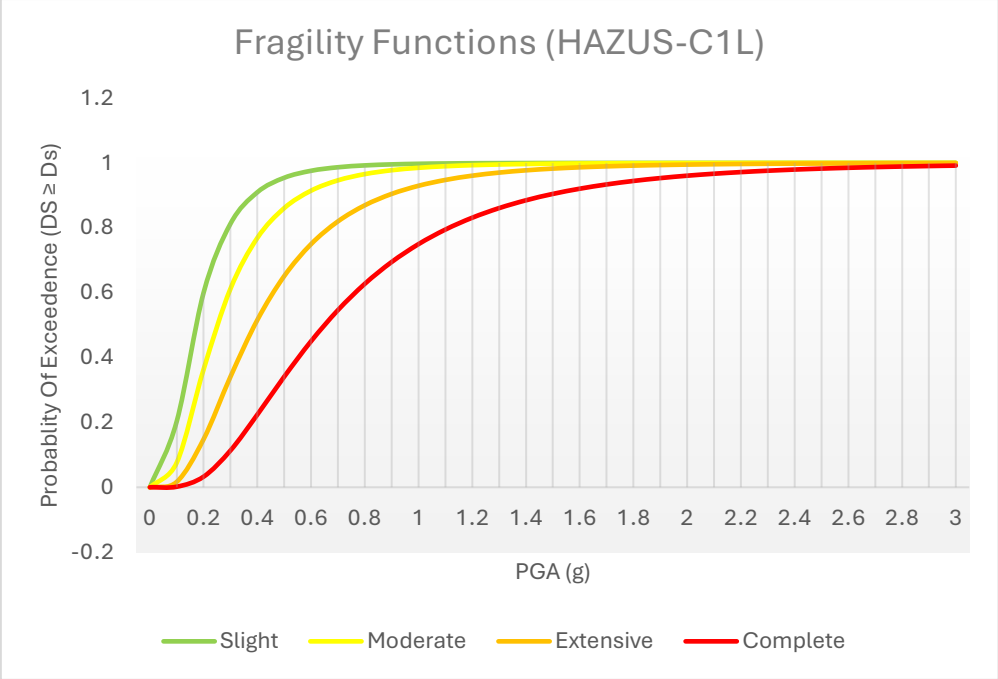


Figure 19 - Fragility Functions from HAZUS Methodology.

5.2 Fragility Functions from ETABS – Methodology

To develop structure-specific fragility functions, nonlinear pushover analysis results obtained from the ETABS model of the selected case study school building explained in Section 4.3 were used. A brief summary of methodology is presented in Figure 20.

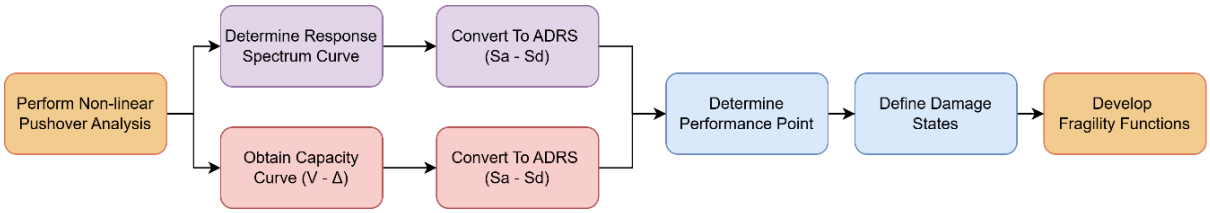


Figure 20 - Framework for Developing Fragility Functions from ETABS

Capacity Curve to ADRS (Acceleration–Displacement Response Spectrum)

The capacity curve obtained from nonlinear pushover analysis, expressed in terms of base shear (V_b) and roof displacement (Δ_{roof}), was transformed into spectral acceleration (S_a) and spectral displacement (S_d) coordinates using the Capacity Spectrum Method (CSM). This procedure converts the multi-degree-of-freedom (MDOF) structural system into an equivalent single-degree-of-freedom (SDOF) system, allowing the structural capacity to be represented in the Acceleration–Displacement Response Spectrum (ADRS) format [2].

As explained by [29], the spectral displacement is obtained as:

$$S_d = \frac{\Delta_{roof}}{\Gamma \Phi_{roof}} \tag{5.2}$$

Where,

- Δ_{roof}= roof displacement obtained from pushover analysis
- Γ= modal participation factor
- Φ_{roof}= modal amplitude at the roof level

In most practical implementations, the mode shape is normalized such that $\Phi_{roof} = 1.0$,

Similarly, the spectral acceleration is calculated as:

$$S_a = \frac{V_b}{\Gamma m^*} \tag{5.3}$$

Where,

- V_b= base shear obtained from pushover analysis
- m^*= equivalent modal mass of the SDOF system
- Γ= modal participation factor

The modal participation factor is determined from the mass distribution and assumed displacement shape as:

$$\Gamma = \frac{\sum m_i \Phi_i}{\sum m_i \Phi_i^2} \tag{5.4}$$

and the equivalent modal mass is given by:

$$m^* = \sum m_i \Phi_i \tag{5.5}$$

Where,

- m_i= mass at level i
- Φ_i= modal displacement at level i

This transformation enables the direct comparison between the structural capacity curve and seismic demand spectra, which is required for performance-based seismic evaluation and for the derivation of fragility relationships [10, 12, 29]. The modal participation factors and modal mass values used in Eq-5.2 to Eq-5.5 for the transformation to ADRS [2] were obtained from the modal analysis results of the ETABS model [18].

Response Spectrum to ADRS (Acceleration–Displacement Response Spectrum)

The conventional response spectrum is typically defined in terms of spectral acceleration (S_a) versus vibration period (T). In order to convert this spectrum into ADRS format, the spectral displacement is calculated from the spectral acceleration using the relationship derived from the dynamic equilibrium of a single-degree-of-freedom system [2].

The spectral displacement is obtained using the following equation:

$$S_d = \frac{T^2}{4\pi^2} S_a g \tag{5.6}$$

Where,

- S_d= spectral displacement
- S_a= spectral acceleration (in units of g)
- T= natural vibration period of the structure
- g= acceleration due to gravity

Performance Points to Damage States

The damage states required for the development of fragility functions were determined from the performance points obtained from the nonlinear pushover analysis [29]. In this study, the bilinear idealized capacity curve generated directly from ETABS according to the ASCE 41-13 NSP procedure was adopted [19]. This curve provides the key structural response parameters which includes the yield displacement (D_y) and the ultimate displacement (D_u) of the structure. The damage state thresholds or median values for developing fragility functions have been adapted from the work of [30] and is shown in Figure 21.

$\overline{\mathrm{Sd}_1} = 0.7D_\mathrm{y}$	Slight
$\overline{\mathrm{Sd}_2} = D_\mathrm{y}$	Moderate
$\overline{\mathrm{Sd}_3} = D_\mathrm{y} + 0.25(D_\mathrm{u} - D_\mathrm{y})$	Severe
$\overline{\mathrm{Sd}_4} = D_\mathrm{u}$	Complete

Figure 21 - Damage State Thresholds Values (Barbat, 2008)

5.3 Fragility Functions from ETABS – Undamaged Structure State

The fragility functions developed in this study are expressed in terms of peak ground acceleration (PGA, g) to facilitate comparison with HAZUS-based seismic vulnerability assessments and to allow consistent probabilistic damage and loss estimation. The conversion procedure of damage state thresholds from Spectral displacement to damage state thresholds of equivalent PGA (g) is based on the Capacity Spectrum Method (CSM) framework, where the structural capacity curve (in terms of spectral displacement, S_d, and spectral acceleration, S_a) is intersected with the seismic demand spectrum [12, 29, 31] as shown in Figure 22.

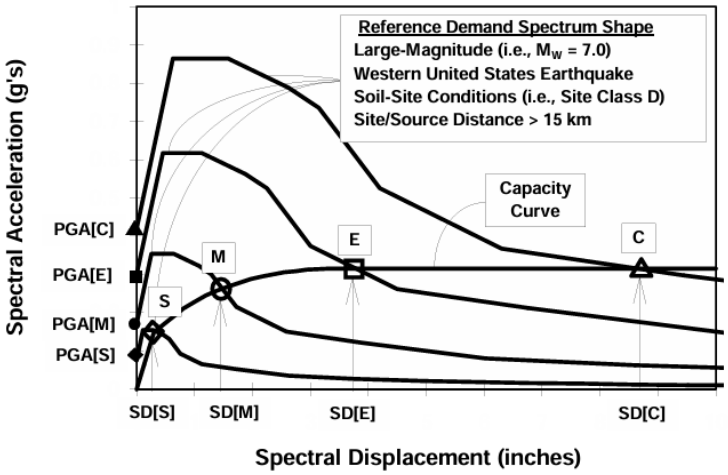


Figure 22 - Representation to find the equivalent median values in terms of PGA (g) (HAZUS)

Therefore, using the prepared framework explained in Section 5.2, the equivalent median values for PGA (g) found are shown in Table 8.

Table 8: Equivalent Medians for PGA (g) for undamaged structure state

Damage State	Spectral Displacement Limits	Equivalent Median Value PGA (g)
Slight	0.07736	0.18500
Moderate	0.11051	0.22824
Extensive	0.14713	0.26169
Complete	0.25699	0.31146

These values were substituted in Eq-(5.1) with β = 0.64 [12] and following fragility curves were developed for undamaged structure state that are shown in Figure 23.

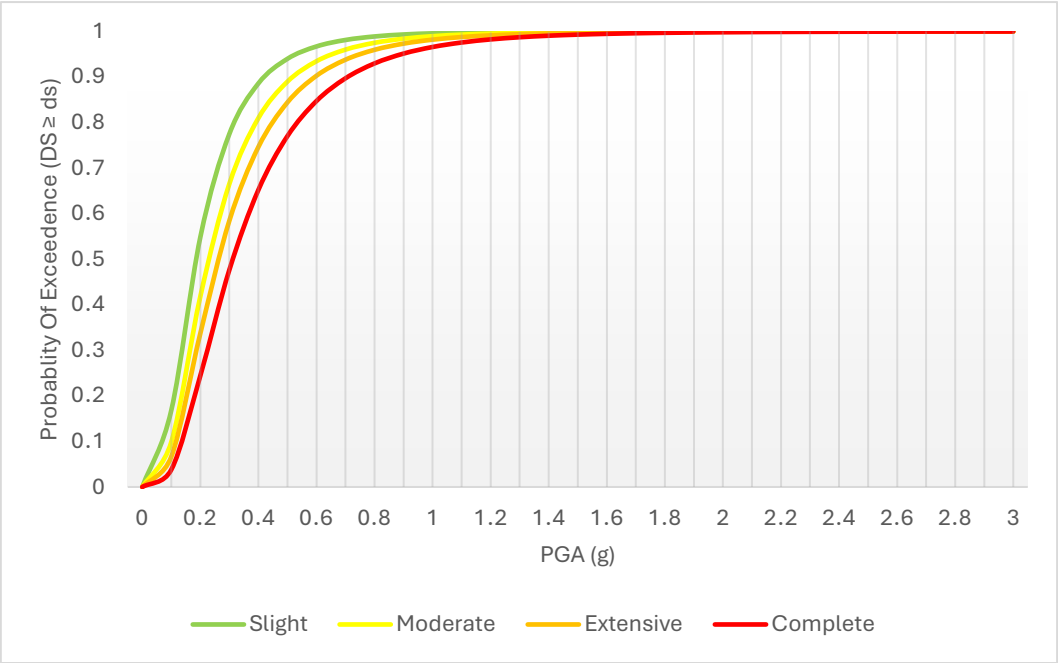


Figure 23 - Fragility Functions for ETABS Undamaged Structure State

5.4 Fragility Functions from ETABS – Damaged Structure State

Similarly, using the same framework described in Section 5.2 and 5.3, the equivalent median values for PGA (g) for damaged structure state found to be are listed in Table 9.

Table 9: Equivalent Medians for PGA (g) for damaged structure state

Damage State	Spectral Displacement Limits	Equivalent Median Value PGA (g)
Slight	0.06066	0.12144
Moderate	0.08666	0.12522
Extensive	0.19068	0.16408
Complete	0.50274	0.26695

These values were substituted in Eq-(5.1) with $\beta = 0.64$ [12] and following fragility curves were developed for damaged structure state that are shown in Figure 24.

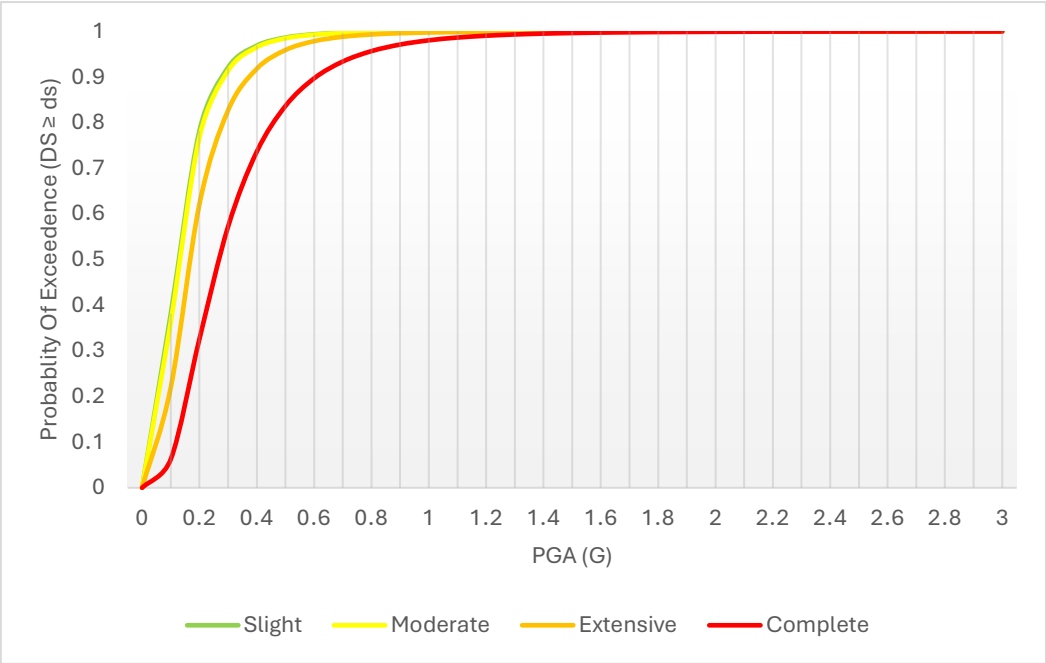


Figure 24 - Fragility Functions for ETABS Damaged Structure State

6 Seismic Risk Assessment of Schools

The seismic risk assessment of the school buildings was conducted to estimate the expected structural damage, economic losses, and potential casualties resulting from earthquake events. This assessment was performed using the fragility functions developed in this study together with the loss estimation relationships provided in the HAZUS Earthquake Loss Estimation Methodology [12]. The objective of this analysis is to quantify the potential seismic risk associated with the large inventory of government school buildings and to identify the level of vulnerability under different structural conditions.

A total of 1806 government school buildings were considered in this study based on the available inventory database. These schools are classified in the School Education and Literacy Department (SELD) database into three structural condition categories [13] and also based on field inspections:

- Satisfactory
- Needs Repair
- Dangerous

These classifications reflect the observed physical condition and structural integrity of the buildings. Many of the school buildings were constructed several decades ago without modern seismic detailing, and field observations indicated varying levels of deterioration such as cracked concrete members, exposed reinforcement, and damaged structural elements.

To incorporate these different structural conditions in the seismic risk assessment, three different sets of fragility functions developed were used in this study. The fragility functions used for each building condition are summarized in Table 10.

Table 10: Fragility Functions Utilization for Different Building Conditions.

Building Condition	Fragility Function Used	Description
Satisfactory	HAZUS Fragility Functions	Represents relatively intact structural condition with minimal or no deterioration
Needs Repair	ETABS Fragility Functions (Undamaged Model)	Represents buildings with moderate deficiencies but still structurally functional
Dangerous	ETABS Fragility Functions (Damaged Model)	Represents buildings with significant structural deterioration

The use of different fragility functions for these building conditions allows the seismic vulnerability assessment to realistically capture the variation in structural performance across the school inventory.

6.1 Economic Loss Estimation

For estimating the direct economic losses, the procedures described in Chapter 15 of the HAZUS Earthquake Loss Estimation Methodology [12] were adopted. HAZUS provides simplified relationships for estimating building repair costs based on the expected structural and non-structural damage states. The economic loss is quantified using repair cost ratios associated with different damage states for specific building occupancy classes. The total building repair cost is estimated by combining three primary components: structural repair cost ratios, acceleration-sensitive non-structural repair cost ratios, and drift-sensitive non-structural repair cost ratios [12].

According to HAZUS methodology [12], the schools are classified as "EDU1" building class as per Table 15.1 and using Table 15.2, 15.3 and 15.4, the cost ratios for "EDU1" building class given are shown in Table 11.

Table 11: Repair Cost Ratios (in % of building replacement cost)

Type of Cost Ratios	Damage States			
	Slight	**Moderate**	**Extensive**	**Collapse**
Structural Repair Cost Ratios	0.4	1.9	9.5	18.9
Acceleration Sensitive Non-structural Repair Cost Ratios	0.7	3.2	9.7	32.4
Drift Sensitive Non-structural Repair Costs	0.9	4.9	24.3	48.7
Total	2	10	43.5	100

The primary inputs that are required to estimate any type of losses for a school building are described in Table 12 [12, 13].

Table 12: Primary input parameters required for the estimation of losses of school buildings.

Input Parameter	Description
School ID	Unique identification number assigned to each school in the inventory database used for the seismic risk assessment.
(Longitude, Latitude)	Geographical coordinates representing the spatial location of the school building.
Building Condition	Structural condition classification of the school building based on field assessment and SELD database categories, including *Satisfactory*, *Needs Repair*, and *Dangerous*.
Peak Ground Acceleration (PGA), g	Site-specific peak ground acceleration corresponding to the seismic hazard level at the school location, expressed in units of gravitational acceleration (g).
Damage State Probability (%)	Probability of the building reaching or exceeding different damage states at the specified PGA level, obtained from the developed fragility functions.

For specifically estimating the economic losses, the inputs required are described in Table 13.

Table 13: Input parameters required for the estimation of direct economic losses of school buildings.

Input Parameter	Description
Total Number of Rooms in the School	Total number of classrooms or functional rooms within the school building, used to estimate the total replacement value of the structure.
Unit Cost of Classroom Construction	Estimated replacement cost associated with constructing a single classroom, used as the basis for calculating the overall building replacement cost.
Repair Cost Ratios	Damage-dependent repair cost fractions representing the portion of replacement cost required to repair structural and non-structural components (from the [12])

For exact PGA (g) values for a specified (Longitude, Latitude), seismic hazard from Global Earth Quake Model [32] was used and it was enhanced by multiplying with Site Amplification factor for site class D as described in [12]. In order to get the approximate idea of unit cost of classroom construction, Tameer-e-Millat Foundation [33] report was referred in which they reported that it cost them 875,250 Rs. to construct the unit classroom which includes everything from grey structure to finishes. Therfore, in simple terms, we can combine all the inputs that are required in Table 12 and Table 13 into one compact equation for the expected economic loss $E[L]$ of a school building:

$$\boxed{E[L] = N_r C_r \cdot \sum_{i=1}^{n} P(D\,S_i)\,RC_i} \tag{6.1}$$

Where:

- $E[L]$ = expected economic loss for the building
- N_r= total number of rooms/classrooms in the building
- C_r= unit cost of constructing a single classroom
- $P(DS_i)$ = probability of the building being in damage state i (from fragility functions)

- RC_i = repair cost ratio associated with damage state i (including structural, acceleration-sensitive non-structural, and drift-sensitive non-structural components)
- n = total number of damage states considered (e.g., Slight, Moderate, Extensive, Complete)

This single Eq-(6.1) captures both the replacement value calculation and the expected loss using damage probabilities and repair cost ratios, exactly as described in HAZUS methodology [12]. The Eq-(6.1) was used in spreadsheet and economic loss was calculated for all schools.

6.2 Fatalities Estimation

For estimating the loss of life or fatalities, the procedures described in Chapter 12 of the HAZUS Earthquake Loss Estimation Methodology [12] were adopted. HAZUS classify the fatalities as Severity-4 casualty and provides simplified relationships for estimating fatalities based on the listed inputs described in Table 14.

Table 14: Input parameters required for the estimation of Fatalities for school buildings population.

Input Parameter	Description
Collapse and No-Collapse Probability	Probability that the building will either collapse or remain standing under the considered seismic hazard (Table 13.8 of [12])
Casualty Rates for Severity 4 (Fatalities)	Fraction of occupants expected to experience severe injuries or fatalities if the building collapses (Table 13.3 to 13.7 of [12]).
Total Population of the School	Total number of occupants (students + staff) exposed to the seismic hazard in the school building.
Estimated Population Distribution at Time of Hazard	Distribution of occupants in different time in the building at the moment of the earthquake, used to refine casualty estimates based on when the hazard occur (Table 13.2 of [12]).

Therefore, in simple terms, we can combine all the inputs that are required in Table 12 and Table 14 into one compact equation for the fatalities $E[F]$ in a school building:

$$E[F] = \mathrm{Pop}_{\mathrm{total}} \cdot \sum_{i=1}^{n} P(DS_i) \cdot CR_i \cdot D_i \tag{6.2}$$

Where:

- $E[F]$ = expected number of fatalities
- $\mathrm{Pop}_{\mathrm{total}}$= total population of the school (students + staff)
- $P(DS_i)$ = probability of the building being in damage state i (from fragility functions)
- CR_i= casualty rate for severity level 4 in state i
- D_i= fraction of occupants present in the building at the time of the hazard (from estimated population distribution)

This single Eq-(6.2) is used to estimate the fatalities for the school building population, exactly as described in HAZUS methodology [12]. The Eq-(6.2) was used in spreadsheet and fatalities ratios were calculated for all schools.

6.3 Loss of Function Time (Downtime) Estimation

Loss of function time for each school can be estimated by multiplying PGA (g) with Building Recovery Time for each damage state specified in Table 15.10 of Hazus-MH MR4 [12]. Therefore, in simple terms, the equation for estimating the downtime $E[F]$ for a school building is:

$$\boxed{E[DT] = \sum_{i=1}^{n} P(DS_i) \cdot BR_i} \tag{6.3}$$

Where:

- $E[DT]$ = expected downtime in days
- $P(DS_i)$ = probability of the building being in damage state i (from fragility functions)
- BR_i= building recovery time in state i

This single Eq-(6.3) is used to estimate the fatalities for the school building population, exactly as described in HAZUS methodology [12]. The Eq-(6.3) was used in spreadsheet and expected downtimes were calculated for all schools in days.

7 Results and Discussion

This section presents the key findings of the study through a series of thematic maps developed from all the working in the study, providing a spatial understanding of the seismic vulnerability and post-earthquake impact on schools across the study area. The study integrates multiple factors including economic losses, human casualties, and operational disruptions to offer a detail assessment of school safety and resilience in the towns of Karachi. All thematic maps use a green-to-red color scale, where green represents the least intense impact and red represents the most severe impact. This visual approach allows for immediate recognition of high-risk zones (Figure 25 to 29).

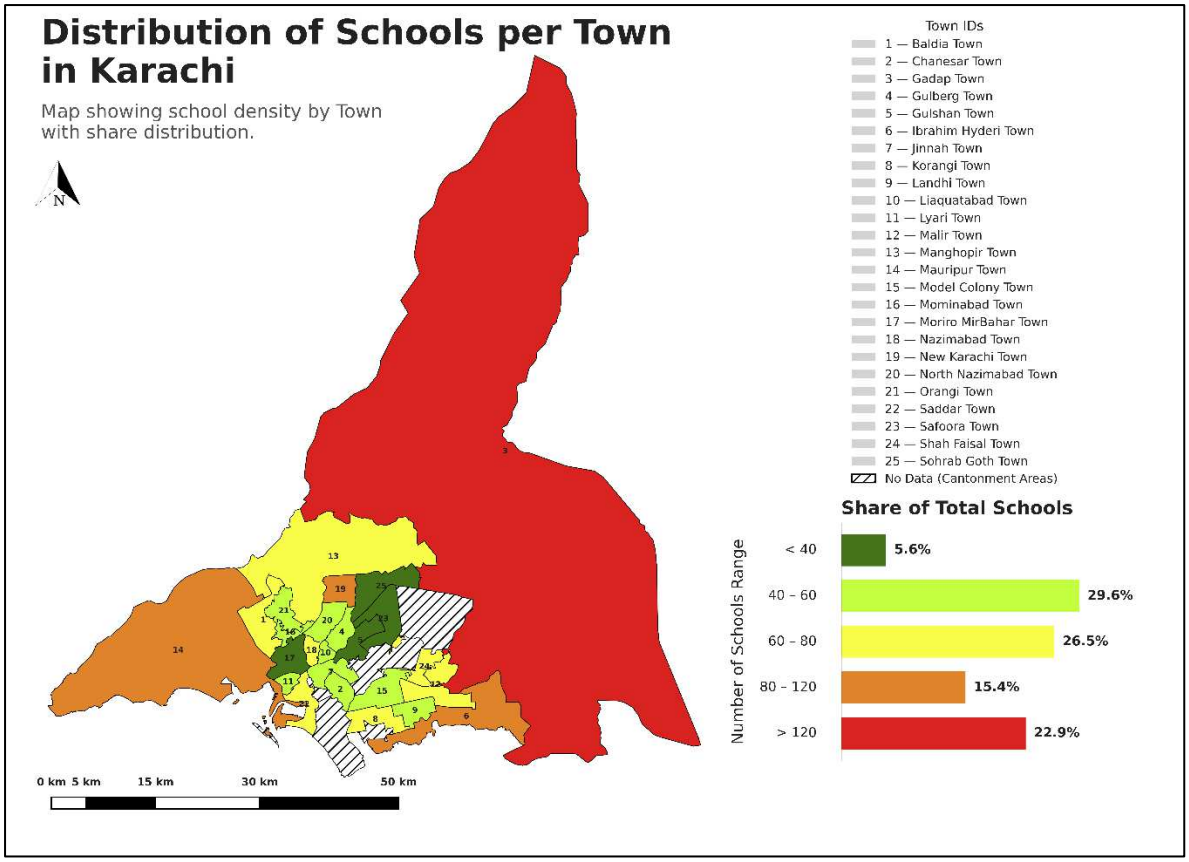


Figure 25 - Map showing No. of Schools per town

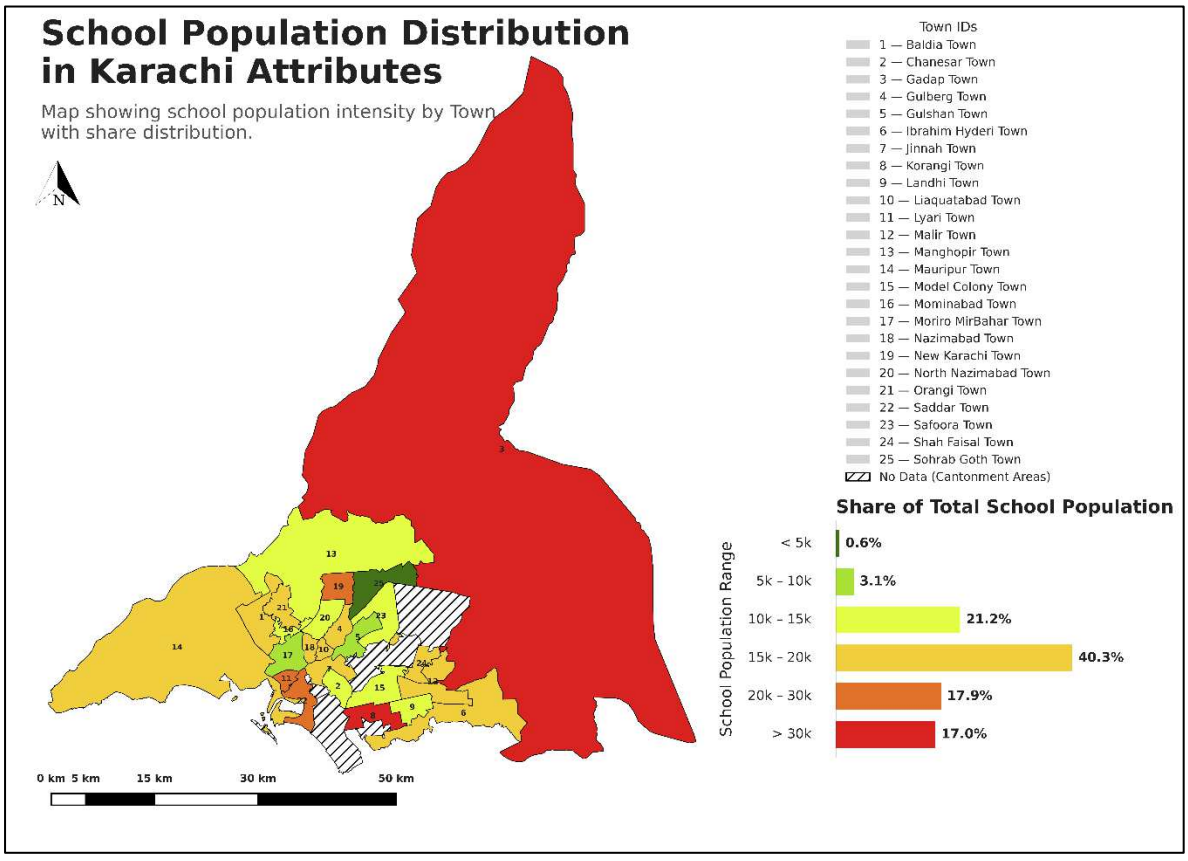


Figure 26 - Map showing School Population per town

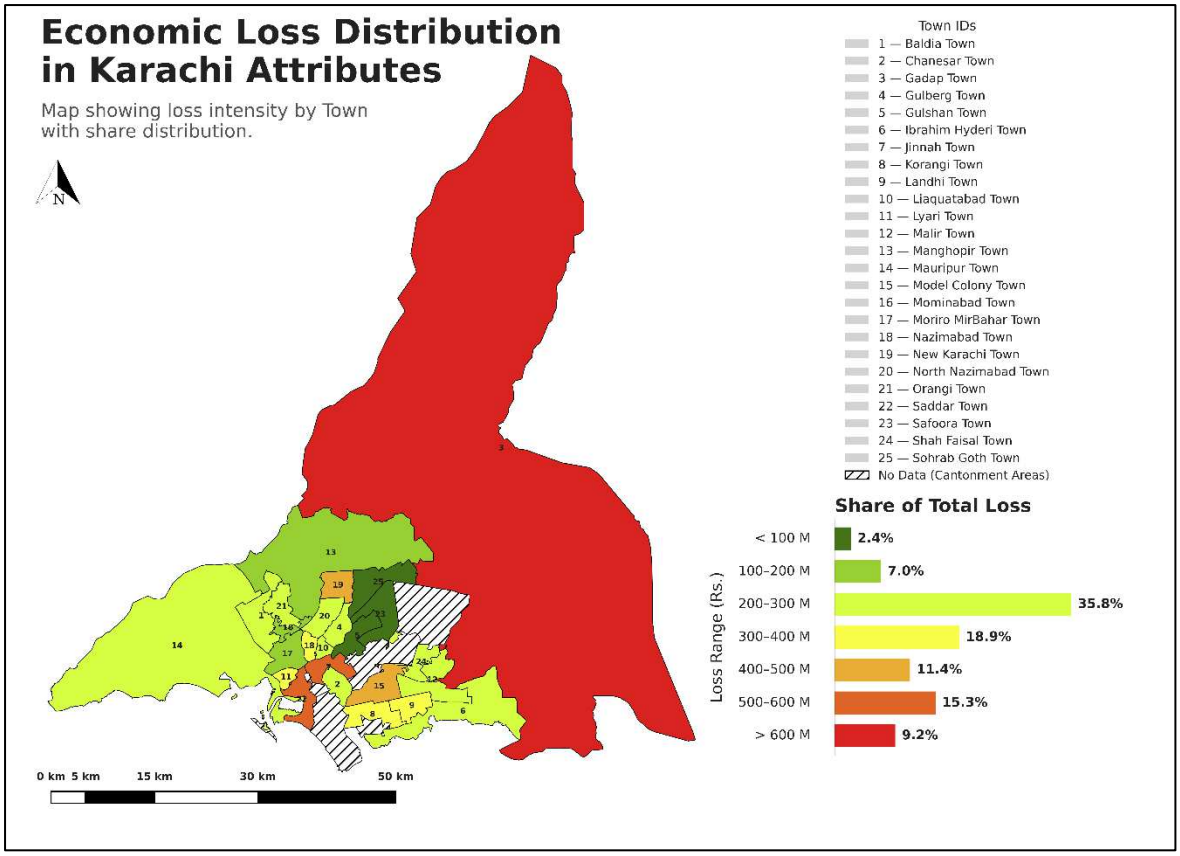


Figure 27 - Map showing Economic Losses per town

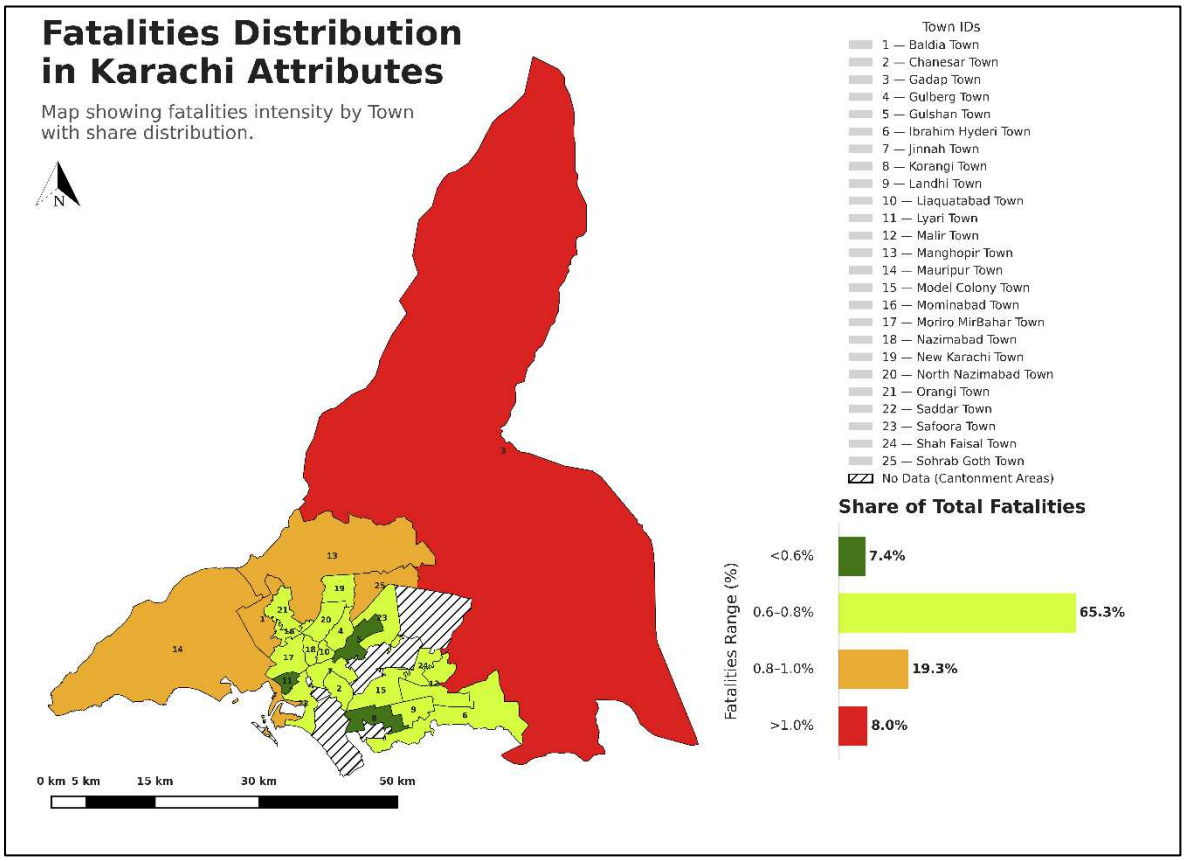


Figure 28 - Map showing Expected Fatalities per town

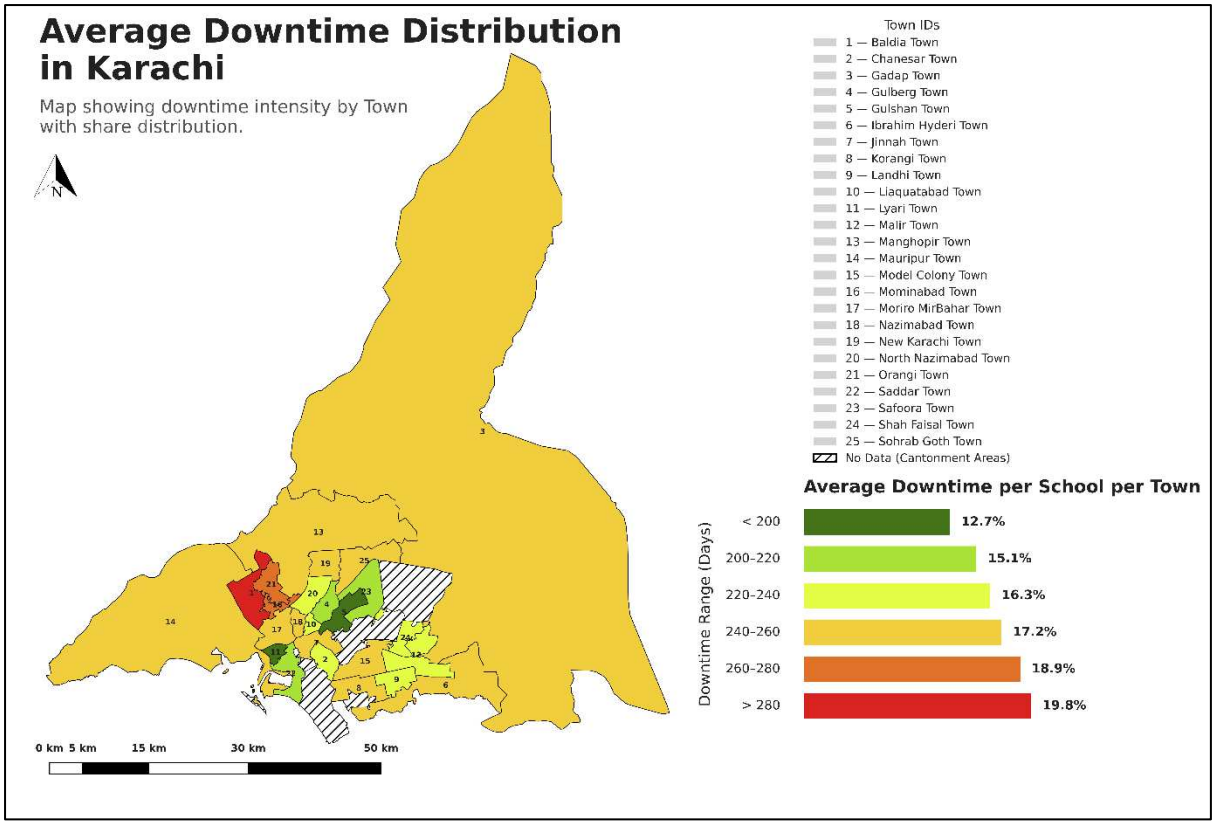


Figure 29 - Map showing Average Downtime per School per town

Figure 25 represents a thematic map showing the total number of public schools in each town of Karachi. The corresponding bar chart (Figure 30) ranks towns by school count, revealing that Gadap Town have the highest number of schools, indicating greater exposure density.

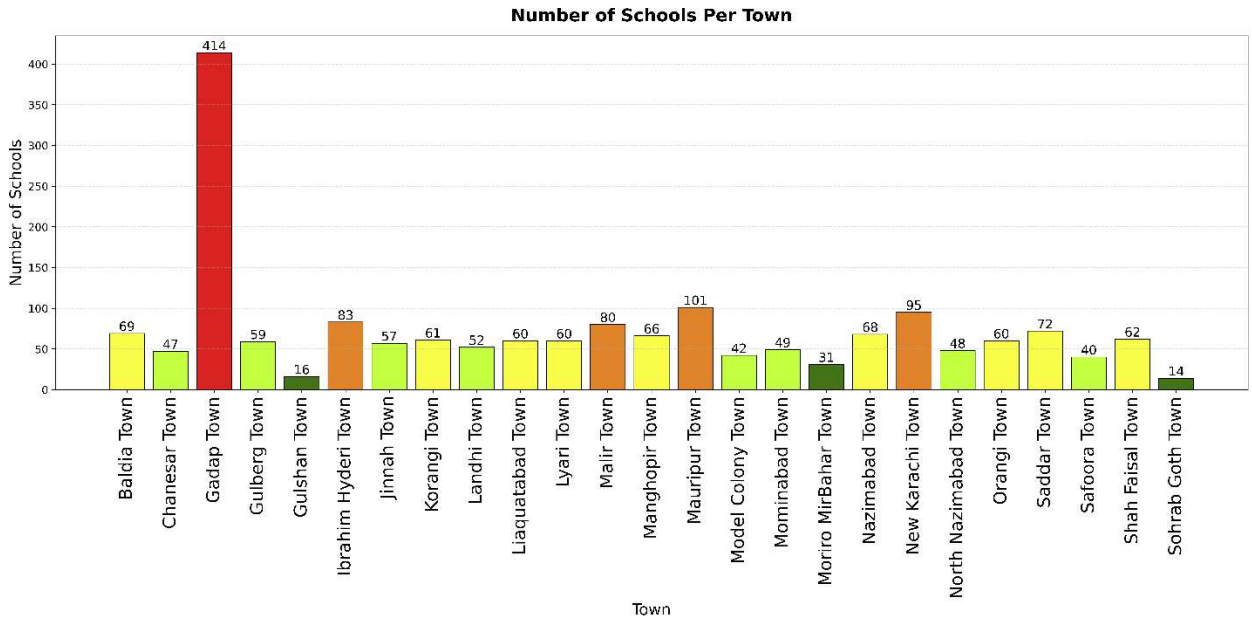


Figure 30 - Bar chart showing no. of schools per town

Figure 26 displays the enrolled student population per town. The bar chart representation shown in Figure 31 highlights that Gadap Town and Korangi Town have the highest student populations,

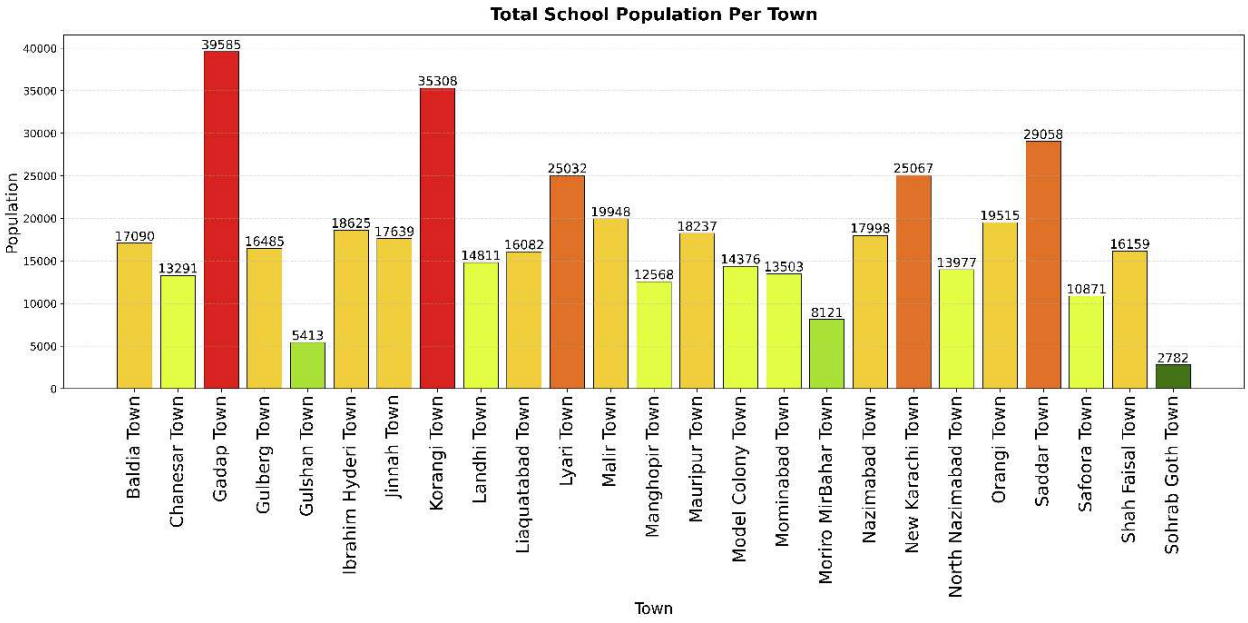


Figure 31 - Bar chart showing total school population per town

Figure 27 maps expected economic losses spatially. The bar chart (Figure 32) ranks towns by estimated loss (PKR Million), identifying Gadap Town, Jinnah Town, and Saddar Town as the most financially vulnerable.

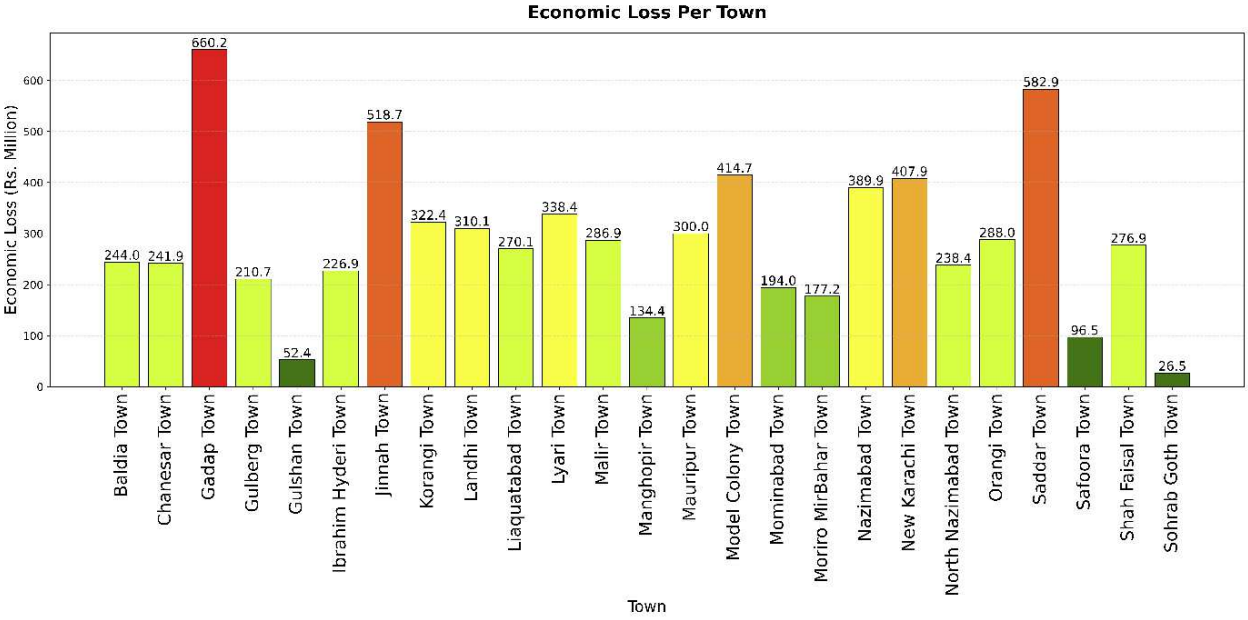


Figure 32 - Bar chart showing total economic loss per town

Fatality estimates are mapped in Figure 28. The bar chart in Figure 33 shows that Gadap Town exhibit the highest expected fatality ratios, exceeding 1.0% of the school population.

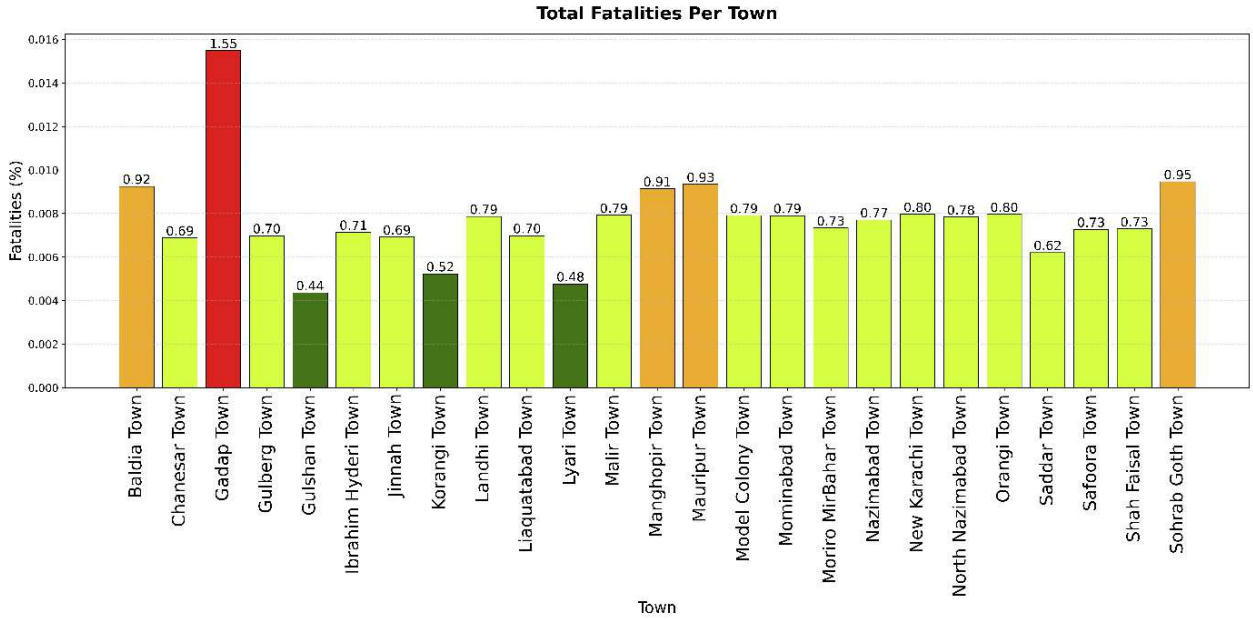


Figure 33 - Bar chart showing expected total fatalities per town

Functional downtime is presented spatially in Figure 29. The bar chart (Figure 34) indicates that schools in Baldia Town are expected to experience the longest recovery periods, exceeding 280 days on average.

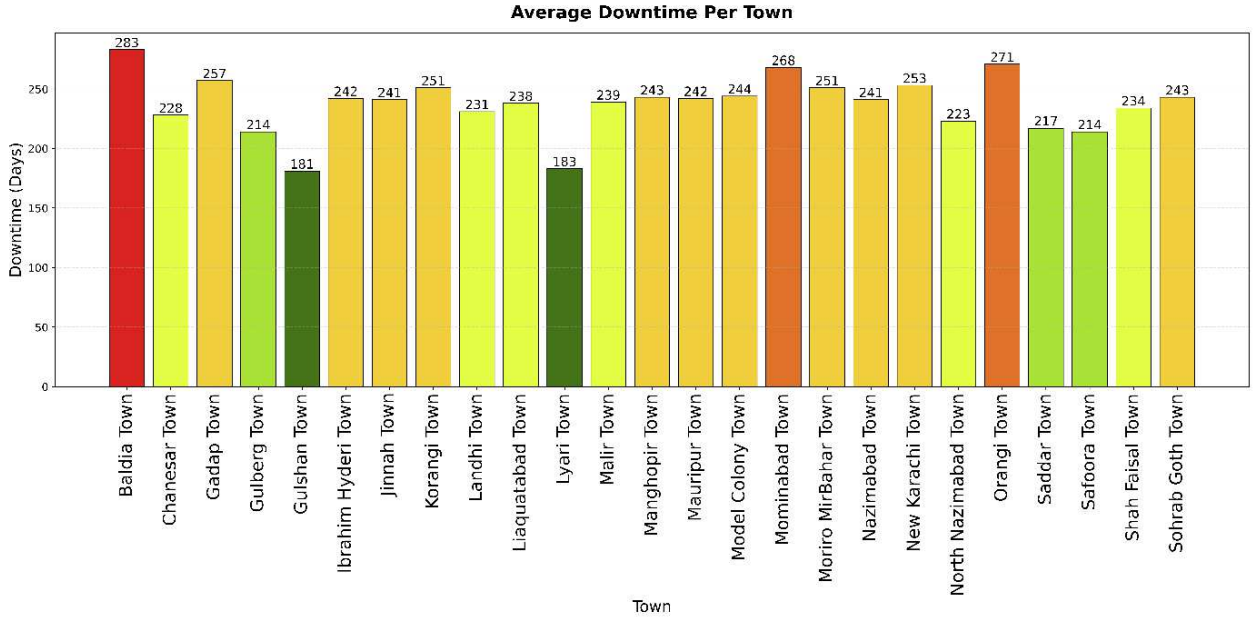


Figure 34 - Bar chart showing average downtime per school in each town

8 Conclusion and Recommendations

This study developed a comprehensive framework for seismic vulnerability and risk assessment of public-school buildings in Karachi by integrating field surveys, nonlinear structural analysis, fragility assessment, and HAZUS-based loss estimation. An inventory of 1,806 RC public school buildings was compiled and validated across all 25 towns of Karachi. Nonlinear pushover analysis of a representative damaged school building demonstrated significant reductions in lateral strength and deformation capacity due to structural deterioration.

Fragility functions were developed using both HAZUS empirical relationships and analytical models derived from ETABS for buildings classified as "Satisfactory," "Needs Repair," and "Dangerous." The results revealed considerable spatial variation in seismic risk across Karachi. Estimated economic losses ranged from approximately PKR 26 million to PKR 660 million per town, fatality ratios generally varied between 0.5% and 1.5%, and functional downtime was estimated between 180 and 280 days per school. Gadap Town was identified as the most critical region in terms of overall seismic risk, while Gulshan Town exhibited comparatively lower risk levels.

The study highlights that buildings categorized as "Dangerous" possess significantly higher probabilities of severe damage and associated losses, emphasizing the urgent need for seismic retrofitting, maintenance, and enforcement of seismic design provisions for school infrastructure in Karachi.

Future studies should extend the framework to other building typologies, particularly unreinforced masonry schools, and incorporate the effects of masonry infill walls in structural modeling. Advanced analysis methods such as nonlinear time history analysis (NLTHA), incremental dynamic analysis (IDA), and fiber-based distributed plasticity models should be adopted for improved accuracy in fragility assessment. Additionally, pounding effects between adjacent buildings and region-specific repair cost databases should be included to enhance loss estimation and overall seismic risk evaluation.

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Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.