

Seismic-Resilient Structural Systems: Geotechnical Engineering

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Abstract

Earthquakes represent one of the most destructive natural hazards, capable of causing severe structural damage, loss of life, and substantial economic disruption. Seismic waves propagating through the ground can induce excessive forces and deformations in buildings, often leading to partial or complete collapse. Statistical records indicate that thousands of earthquakes occur globally each year, including several major events that result in significant damage. Past earthquake disasters have repeatedly demonstrated that structural failure, particularly of inadequately designed buildings, is the primary cause of casualties, thereby emphasizing the necessity for earthquake-resistant construction practices. Although it is not feasible to design structures that are entirely immune to seismic damage, earthquake-resistant design focuses on enhancing structural performance and ensuring life safety under expected seismic demands. Current building codes require structures to be designed to withstand the maximum credible earthquake with a reasonable probability of occurrence at a given site. Modern earthquake engineering has evolved through the integration of experimental investigations, numerical simulations, and observations from historical seismic events to achieve reliable and efficient seismic performance. This paper discusses various techniques and design strategies aimed at improving the seismic resistance of structures. Earthquake-resistant structural design has emerged as a multidisciplinary field, incorporating advancements in probabilistic seismic analysis, performance-based design methodologies, innovative structural systems and energy dissipation devices, and the use of non-conventional materials. Furthermore, recent developments in advanced analytical tools enable more accurate prediction of structural response by accounting for material nonlinearity, strength and stiffness degradation under cyclic loading, geometric effects, and, critically, soil–structure interaction. These advancements collectively contribute to the development of safer and more resilient structures in seismically active regions.

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INTRODUCTION

Earthquake-resistant construction involves systematic planning, analysis, and design of structures to withstand seismic ground motions with controlled damage while ensuring the safety of occupants. During earthquakes, buildings are subjected to dynamic lateral forces that may exceed those produced by gravity loads. If these forces are not adequately accounted for in design, they can lead to severe structural distress or collapse.

Therefore, earthquake-resistant structures are required to possess sufficient strength, ductility, stiffness, and energy dissipation capacity to perform satisfactorily during seismic events [1–3].

The seismic performance of a structure is influenced not only by analytical design parameters but also by construction practices, material quality, reinforcement detailing, and strict compliance with codal provisions. Historical earthquake damage assessments reveal that structural failures are frequently associated with poor workmanship, inadequate detailing, substandard materials, and a lack of quality control, particularly in developing regions. Such deficiencies significantly reduce the intended seismic resistance of buildings, even when designed according to modern codes [4].

In the present study, two reinforced concrete building models—a mid-rise G+4 structure and a low-rise G+1 structure—are considered for seismic analysis and comparison. The buildings are designed to resist both gravity and lateral seismic loads using the equivalent static method in accordance with relevant Indian Standards, namely IS 1893 (Part 1) and IS 13920. Structural configuration, member dimensions, and reinforcement detailing are incorporated to assess the effectiveness of the buildings in resisting seismic forces and limiting lateral displacements [5].

Project Building Details

1. G+4 Building

- Plan dimensions: 14 m × 8 m
- Number of storeys: Ground + 4
- Ground floor height: 3.5 m
- Typical floor height: 3.0 m
- Total building height: 15.5 m

2. G+1 Building

- Single-storey low-rise structure
- Scaled model adopted for comparative evaluation of seismic behavior.

LITERATURE REVIEW

Traditional construction practices in many seismically active regions incorporate empirically developed earthquake-resistant features based on local experience, materials, and cultural knowledge. These vernacular systems typically emphasize flexibility, low mass, and structural continuity, which contribute to improved seismic performance. Recent studies highlight the potential of integrating such indigenous techniques into modern construction to enhance seismic safety while preserving cultural heritage [6].

Steel structures are widely recognized for their superior ductility and energy absorption capacity under seismic loading. However, damage observed during major earthquakes, such as the 1994 Northridge and 1995 Kobe events, exposed vulnerabilities in conventional welded steel connections. Consequently, contemporary research has focused on the development of improved connection detailing, smart materials, and energy-dissipating devices within a performance-based design framework to enhance resilience and minimize post-earthquake repair costs [7].

Probabilistic seismic risk assessment and performance-based design methodologies have gained prominence as they provide a more comprehensive evaluation of structural behavior under inherent uncertainties in seismic demand and material properties. These approaches overcome the limitations of deterministic design by enabling realistic prediction of damage states and post-earthquake functionality [8].

The performance-based plastic design (PBSD) approach introduces a rational design methodology by predefining target drift limits and desired yield mechanisms. This method has demonstrated enhanced seismic performance for reinforced concrete and steel moment-resisting frames, particularly

in medium- and high-rise buildings, while reducing the complexity associated with iterative design procedures [9].

Precast concrete construction systems offer advantages in terms of construction speed, quality control, and sustainability. However, their seismic performance is highly dependent on the effectiveness of joint detailing and energy dissipation mechanisms. Recent advancements in connection design have enabled precast systems to achieve satisfactory performance even in high seismic zones [10].

Seismic isolation and supplemental energy dissipation systems, such as base isolators and dampers, have proven effective in reducing seismic forces transmitted to superstructures. These systems improve structural performance and post-earthquake operability, and their adoption is increasingly encouraged in modern seismic design standards to enhance overall resilience.

Recent studies also highlight the importance of comparing earthquake-resistant tall buildings in different seismic zones in India to understand optimization of design strategies and construction practices [7].

In precast buildings, research trends emphasize energy-dissipating dry connections, optimization techniques, and prevention of progressive collapse, indicating the growing need for connection-focused design strategies [9].

Self-centering rocking systems have emerged as a promising low-damage seismic design alternative, offering rapid post-earthquake recovery. However, wider adoption is limited due to implementation challenges and a lack of design familiarity in industry practice [10].

GRAVITY LOAD ANALYSIS

Load Analysis

Load analysis involves determining the forces acting on each structural element. Gravity loads consist of dead loads (self-weight of structural components such as slab, beams, columns, finishes, and services) and live loads (occupants and movable loads). These loads act on slabs and are transferred to beams and columns.

Load Calculations for G+4 Building

Slab thickness	=	0.15 m
Beam size	=	0.25 m × 0.40 m
Column size	=	0.40 m × 0.40 m
Live load	=	2 kN/m ²
Floor finish load	=	1 kN/m ²
Dead load	=	3.75 kN/m ²
Total load (W)	=	6.75 kN/m ²

Load Distribution

Shorter span load:	$W \times L_x / 3$
Longer span load:	$[W L_x / 6] [(3 - (L_x / L_y)^2)]$
Example (Slab 1: $L_x = 3.71$ m, $L_y = 5.04$ m):	
Shorter span	= 8.35 kN/m ²
Longer span	= 10.26 kN/m ²

2D Frame Analysis

The building frame was analyzed using Kani's moment distribution method, suitable for continuous multi-storey frames.

LATERAL LOAD ANALYSIS

Seismic loads on buildings can be evaluated using two major methods: the equivalent static analysis method and dynamic analysis (response spectrum and time history methods). The equivalent static method is commonly used for regular, medium-height buildings due to its simplicity. However, for irregular or tall structures, dynamic analysis is required for accurate seismic response assessment as per IS 1893 (Part 1): 2016.

Design Base Shear

The design seismic base shear (V_e) is computed using:

$$V_b = A_h \times W$$

where,

$$A_h = Z/2 \times I/R \times S_a/g$$

Z, Seismic zone factor (depends on earthquake intensity of region).

I, Importance factor (higher for essential and critical buildings).

R, Response reduction factor (depends on ductility and structural system).

S_a/g , Average response acceleration (depends on natural period and soil type).

The natural time period (T) is estimated using IS 1893 empirical expressions based on building height and frame type.

Seismic weight (W) is calculated from:

- Dead load (self-weight of slab, beams, columns, and walls).
- Live load (25% considered on the roof as per code).
- Floor finish load.

The base shear is then vertically distributed among storeys using:

$$Q_i = W_i h_i^2 / \sum W_i h_i^2 \times V_b$$

Lateral Load Analysis: Portal Frame Method

For multi-storey moment-resisting frames, the portal frame method is adopted as an approximate lateral load analysis technique (suitable up to 25 storeys).

Key Assumptions

1. Points of contra-flexure occur at the mid-height of columns and mid-span of beams.
2. Storey shear is shared so that interior columns carry twice the shear of exterior columns.

Steps

1. Distribute storey shear among columns.
2. Compute column bending moments: $M = V \times H/2$.
3. Apply joint equilibrium to determine beam moments.
4. Beam shear: $V_b = 2M/L$.
5. Determine axial forces from the equilibrium of joint forces.

This method provides bending moments, shear forces, and axial forces necessary for member design.

DESIGN OF STRUCTURE

Aim of Design

Structural design aims to ensure that the structure remains safe, serviceable, and durable during its intended life. It should withstand all expected loads with adequate safety against collapse, excessive deflection, cracking, fire, and accidental effects. The design methods used are:

1. Limit State Method (adopted in this project, as per IS 456:2000).
2. Working Stress Method.

The limit state method provides a rational and probabilistic approach, ensuring both safety (ultimate limit state) and usability (serviceability limit state).

Limit State Method

The limit state method ensures that the structure:

- Does not reach a failure condition during its design life.
- Resists all anticipated loads safely.
- Satisfies serviceability requirements like controlled deflection and cracking.
- Maintains structural integrity during accidental conditions (fire, local failure, etc.).

Major limit states considered:

- Collapse (flexure, compression, shear, torsion).
- Serviceability (deflection and cracking).

Structural Components Designed

The structural elements were designed in this work using IS 456:2000.

Limit State Method

The limit state method includes slabs, beams, columns, and footings.

Design of Slabs

Reinforced concrete slabs are designed as one-way or two-way based on span ratios. In this project, slab panels S7, S3, and S2 were identified as two-way slabs ($L_y/L_x < 2$). Typical design steps followed (as per IS 456:2000):

1. Determine effective depth using the span-to-depth ratio.
2. Calculate dead and live loads.
3. Obtain design bending moments using moment coefficients (Annex D).
4. Provide reinforcement based on the required steel area and minimum reinforcement criteria (Table 1).

Design of Beam

Beam size provided: 250 mm × 400 mm, span 7.86 m.

Factored Load: 25.44 kN/m

Ultimate bending moment: 65.48 kNm < moment capacity 138 kNm, thus safe.

Reinforcement Provided

- 6 bars of 16 mm Ø at the tension zone.
- Deflection criteria satisfied as per IS 456:2000.

Design of Column

- Column size: 400 mm × 400 mm, height 3.5 m.
- The column is short (effective length ratio <12).
- Subjected to axial load 108.85 kN with biaxial bending.

Table 1. Required steel area and minimum reinforcement criteria.

Slab panel	X-direction	Y-direction
S7 (edge slab)	8 mm @ 260 mm c/c	8 mm @ 280 mm c/c
S3 (middle slab)	8 mm @ 100 mm c/c	12 mm @ 160 mm c/c
S2 (corner slab)	8 mm @ 120 mm c/c	10 mm @ 140 mm c/c

Reinforcement Provided

- 16 bars of 18 mm \varnothing ($A_{st} \approx 4071 \text{ mm}^2$).
- Lateral ties: 10 mm \varnothing @ 100 mm spacing.

Column satisfies interaction criteria as per SP-16.

METHODS OF DESIGNING EARTHQUAKE-RESISTANT BUILDINGS**Earthquake-Resistant Structural Techniques**

Earthquake-resistant design aims to provide buildings with adequate strength, stiffness, and ductility to resist seismic forces. While conventional design focuses on strengthening structural members and connections, advanced earthquake-resistant techniques aim to reduce the seismic forces transmitted to the building itself.

The two major modern techniques used are:

1. Base isolation.
2. Energy dissipation (damping) devices.

SEISMIC RESPONSE CONTROL TECHNIQUES**Base Isolation Method**

Base isolation is an effective seismic protection technique in which the superstructure is decoupled from ground motion by installing specially designed isolation bearings between the structure and its foundation. These isolators are characterized by high vertical stiffness to safely support gravity loads and low horizontal stiffness to permit lateral flexibility during seismic events.

Working Principle

During an earthquake, ground motion is largely absorbed by the isolators, allowing the building above to experience significantly reduced motion. As a result, the isolated structure exhibits:

- Reduced acceleration demand.
- Lower inertial forces.
- Substantially decreased structural deformation.

By concentrating deformation within the isolation layer rather than the superstructure, base isolation minimizes damage to structural and non-structural components and enhances post-earthquake functionality.

Energy Dissipation Devices

Despite the effectiveness of base isolation systems, some seismic energy may still be transmitted to the structure. Supplemental energy dissipation devices, commonly referred to as dampers, are used to absorb and dissipate this energy, thereby reducing vibrations and structural demand (Table 2).

These devices enhance the damping capacity of structures and improve seismic performance by limiting displacement and force demands.

Table 2. Common types of damping devices.

Damper type	Energy dissipation mechanism
Friction dampers	Sliding friction between contact surfaces
Metallic dampers	Yielding and plastic deformation of metal elements
Viscoelastic dampers	Shear deformation of polymer-based materials
Viscous dampers	Resistance due to fluid flow within a cylinder

Fluid Viscous Dampers and Bracing Systems

Fluid viscous dampers are widely used in combination with bracing systems to control structural response under seismic loading. These dampers dissipate energy by forcing a viscous fluid through internal valves, converting kinetic energy into heat.

When installed diagonally between beams and columns, fluid viscous dampers:

- Reduce lateral displacements.
- Increase effective damping.
- Minimize damage to beams, columns, and beam–column joints.

This system is particularly effective for both retrofitting existing buildings and enhancing the seismic performance of new constructions.

EFFECT OF EARTHQUAKE ON REINFORCED CONCRETE BUILDINGS

Reinforced concrete (RC) buildings are composed of slabs, beams, columns, and foundations that collectively resist gravity and lateral loads. During an earthquake, horizontal inertia forces are generated primarily at floor levels due to ground acceleration. These forces are transferred from slabs to beams, then to columns, and finally to the foundation. Consequently, lower storey columns are subjected to higher seismic demands and must be designed with adequate strength and ductility.

Floor Slabs

Floor slabs generally act as rigid diaphragms, ensuring uniform lateral displacement of all vertical elements at a given level. This diaphragm action facilitates the effective distribution of seismic forces throughout the structure.

Masonry Infill Walls

Masonry infill walls contribute additional lateral stiffness and share seismic forces with the RC frame. However, due to their brittle nature, infill walls tend to crack under excessive deformation and behave as sacrificial elements. Irregular distribution of infill walls may introduce torsional effects and short-column behavior, leading to localized damage.

Earthquake Loads Versus Gravity Loads

Unlike gravity loads, which induce unidirectional bending, seismic loads cause stress reversals in structural members. Therefore, beams and columns must be reinforced on both faces to resist cyclic loading and prevent brittle failure.

Strength Hierarchy (Strong Column–Weak Beam Concept)

To ensure ductile behavior, columns must be designed stronger than beams, and foundations stronger than columns. This hierarchy ensures that plastic hinges form in beams rather than columns, preventing storey mechanisms and progressive collapse.

SEISMIC DESIGN PHILOSOPHY

Earthquake-Resistant Design Concept

Earthquake-resistant design is based on the understanding that strong earthquakes are infrequent, yet structures must not collapse when such events occur. Buildings are designed to be earthquake-resistant rather than earthquake-proof.

The intended performance objectives are:

- *Minor earthquakes*: No structural damage.
- *Moderate earthquakes*: Repairable structural damage.
- *Severe earthquakes*: Significant damage permitted, but collapse must be prevented.

Controlled cracking is acceptable; however, failure of primary load-carrying elements, especially columns, is unacceptable. Ductility is a key requirement, allowing structures to undergo large deformations without sudden failure.

Major Components in the Model System

1. Base isolator flexible bearings are installed between the foundation and superstructure to reduce transmission of seismic vibrations.
2. RS-775 DC motor (12 V) used in the experimental model to generate controlled mechanical motion.
3. Ball bearings reduce friction and ensure smooth rotational movement in the system.
4. AC to DC power adapter (12 V) converts alternating current supply into direct current for operating the motor and associated components.

Working Principle of Vibrational Control Devices

Vibration control devices, such as dampers, are installed between beams and columns to absorb seismic energy. These devices typically contain pistons moving through viscous fluids, converting vibrational energy into heat. This mechanism significantly reduces structural response during earthquakes and strong winds, particularly in high-rise buildings, thereby protecting structural elements and interior components and ensuring post-event usability.

Advantages and Disadvantages of Earthquake-Resistant Buildings

Advantages

- Minimized structural damage under seismic loading.
- Enhanced durability and reduced long-term maintenance.
- Prevention of collapse and protection of human life.
- Continued functionality of critical facilities such as hospitals.
- Reduced insurance risk and improved user confidence.

Disadvantages

- Higher initial construction cost (approximately 3–5%).
- Requirement for skilled design and construction practices.
- Periodic inspection and maintenance are needed.
- Possible impact on architectural aesthetics.
- Increased structural weight due to additional reinforcement.

CONCLUSION

The present study involves the analysis and design of RC buildings subjected to gravity and seismic loads in accordance with relevant Indian Standards. Gravity load analysis was carried out manually as per codal provisions to determine bending moments and design forces. Seismic load analysis was performed in accordance with IS 1893 (Part 1), and structural design was executed following limit state design principles. The structural components, including slabs, beams, and columns, were found to be safe with respect to strength, deflection control, and serviceability requirements. Overall, the designed structures are capable of safely resisting all loads expected throughout their design life.

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