

ADVANCED EARTHQUAKE ENGINEERING

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Abstract: *Advanced Earthquake Engineering focuses on understanding and mitigating the risks associated with seismic activities. This field encompasses the study of ground motion, structural response, and the development of innovative design methodologies to enhance resilience in buildings and infrastructure. Recent advancements include the integration of computational simulations, seismic hazard analysis, and performance-based design approaches to predict and withstand earthquake impacts. Emerging technologies such as base isolation systems, energy-dissipating devices, and smart materials are revolutionizing the design of earthquake-resistant structures.*

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I. Introduction

Earthquakes are among the most devastating natural disasters, capable of causing significant loss of life, property damage, and disruptions to society. Advanced Earthquake Engineering is a multidisciplinary field dedicated to understanding seismic phenomena and designing solutions to mitigate their effects on structures and infrastructure. It builds upon fundamental principles of geophysics, structural engineering, and materials science to enhance the safety and functionality of buildings and systems in seismically active regions.

Overview

Advanced Earthquake Engineering is a specialized field dedicated to understanding and mitigating the impacts of seismic activities on infrastructure. It combines principles of structural engineering, geology, and material science with advanced technologies to enhance the resilience and safety of buildings, bridges, and other structures.

1. Significance of earthquake engineering in mitigating seismic risks

Earthquake engineering plays a crucial role in reducing the impact of seismic events on human lives, infrastructure, and the economy. By combining principles of engineering, geology, and advanced technologies, this discipline aims to create resilient structures and systems capable of withstanding earthquakes. The significance of earthquake engineering can be summarized as follows:

Protection of Human Lives

- Designing structures to prevent collapse during earthquakes minimizes casualties.

- Ensuring the safety of critical facilities like hospitals and emergency shelters enhances disaster response and recovery.

Infrastructure Resilience

- Developing earthquake-resistant buildings, bridges, and utilities prevents widespread destruction.
- Implementing retrofitting techniques strengthens existing structures, extending their lifespan and usability.

Economic Benefits

- Reducing damage to infrastructure lowers repair and reconstruction costs.
- Preventing business interruptions and economic losses during seismic events supports economic stability.



Figure 1: Earthquake Engineering

2 Objectives of Earthquake Engineering

- **Minimizing Loss of Life and Injury:** One of the primary objectives is to design and construct buildings and infrastructure that can protect occupants and the general public during an earthquake, thereby minimizing the risk of injury and fatalities.
- **Protecting Infrastructure and Assets:** Earthquake engineering aims to safeguard critical infrastructure, including hospitals, schools, and communication

systems, to ensure that they remain operational after an earthquake.

- **Economic Protection and Loss Reduction:** Reducing the economic impacts of earthquakes by ensuring buildings and infrastructure are resilient, preventing severe damage, and minimizing repair costs.
- **Improving Seismic Resilience of Communities:** Earthquake engineering seeks to ensure that communities can recover quickly after a seismic event by strengthening existing structures and adopting resilient urban planning practices.
- **Sustainable and Adaptable Engineering Practices:** The objective also includes promoting sustainable engineering solutions that are adaptable to varying seismic conditions and evolving technologies, thus ensuring long-term resilience and efficiency.

3 History and Evolution of Earthquake Engineering

The history and evolution of earthquake engineering traces its origins to ancient civilizations, where basic techniques for withstanding seismic forces were employed in structures like temples and homes, particularly in regions like China, Greece, and Japan. As scientific understanding of earthquakes grew, especially after the devastating 1755 Lisbon earthquake, the need for more resilient buildings became clear. By the late 19th and early 20th centuries, advancements in seismology and structural design began to shape modern earthquake engineering, with innovations such as brick vaults and arches to better absorb shock. The 1906 San Francisco earthquake marked a turning point, leading to the development of more formal seismic building codes. Throughout the 20th century, the field saw major advancements, including the introduction of base isolation systems and the use of high-strength materials.

Early Approaches to Earthquake Resistance

- Stone and brick with arches and vaults were used to distribute loads and absorb shock in ancient Greece and Rome.
- Wooden construction in Japan and China was preferred because wood naturally absorbs and dissipates seismic energy.
- Techniques like interlocking beams and foundations were developed to allow buildings to move during tremors.
- Adobe brick construction in the Middle East was flexible enough to bend without cracking, providing resistance to seismic forces.
- These methods were based on practical experience and trial-and-error, rather than scientific understanding of seismic forces.

- The focus was on creating flexible structures capable of absorbing and dissipating energy during earthquakes.

Milestones in Earthquake Engineering Research

Milestones in earthquake engineering research have significantly advanced the field, contributing to improved safety and resilience in structures. Here are some key milestones:

- **1755 Lisbon Earthquake:** The first major event to spark widespread interest in earthquake-resistant construction, highlighting the need for buildings to withstand seismic forces and inspiring early seismic engineering efforts.
- **1906 San Francisco Earthquake:** A pivotal moment in earthquake engineering research, as it led to significant advancements in understanding the effects of earthquakes on structures and the establishment of more robust building codes and design practices.
- **1930s to 1940s – Development of Seismic Design Codes:** Following the San Francisco earthquake, building codes began to incorporate provisions for seismic design, focusing on structural integrity during earthquakes.
- **1940s to 1950s – Introduction of Earthquake-Resistant Design Principles:** Engineers began to develop guidelines for designing structures that could resist earthquakes, incorporating ideas like reinforced concrete and flexible materials to improve the performance of buildings under seismic stress.

Development of Seismic Building Codes

The development of seismic building codes has evolved in response to significant earthquake events, technological advancements, and an increasing understanding of earthquake dynamics. Here are key stages in the development of seismic building codes:

- **Pre-1900s – Lack of Formal Codes:** Early construction techniques were largely based on local traditions and empirical knowledge, with no formalized building codes specifically addressing seismic risks. Structures were often built using flexible materials like wood, but there was no standardized approach to earthquake resistance.
- **1906 San Francisco Earthquake:** The devastation caused by the 1906 earthquake highlighted the urgent need for seismic design standards. Although there were no formal seismic codes at the time, the event significantly raised awareness and spurred efforts to study earthquake effects on buildings and infrastructure.
- **1930s – Early Seismic Code Development:** In the aftermath of the 1933 Long Beach earthquake in California, which caused significant damage, the need for formal seismic codes began to be recognized. The **Uniform Building Code (UBC)**, first published in 1927 and revised in 1935, started

including provisions for earthquake resistance, focusing on the structural integrity of buildings during seismic events.

4 Seismic Hazard and Risk Assessment

Seismic hazard assessment involves evaluating the potential for earthquakes to occur in a given region and understanding the associated ground motions (shaking) that can impact structures. This process is based on the following key factors:



Figure 3: Seismic Risk Assessment

Methods of Assessing Earthquake Risk

There are several methods of assessing earthquake risk, each involving different approaches to evaluate seismic hazards, vulnerabilities, and potential consequences. These methods help guide decision-making for earthquake preparedness, mitigation, and response. Here are the primary methods:

- **Seismic Hazard Mapping:** Identifies regions that are prone to earthquakes based on past seismic activity, fault lines, and geological features.
- **Probabilistic Seismic Hazard Analysis (PSHA):** Uses statistical methods to estimate the likelihood of earthquakes of different magnitudes in specific areas over a period.
- **Fault Line Mapping:** Locates and monitors active fault zones that are potential sources of seismic activity.
- **Seismic Microzonation:** Divides regions into smaller zones based on soil conditions, local fault lines, and expected ground shaking to predict damage.
- **Ground Shaking Intensity:** Assesses the intensity and distribution of ground shaking that can occur during an earthquake, affecting structures and infrastructure.
- **Building Vulnerability Assessment:** Evaluates the resilience of existing buildings and structures to seismic events based on materials, age, and design.
- **Structural Health Monitoring:** Uses sensors to monitor the condition of buildings and infrastructure to understand their seismic vulnerability.

- **Historical Earthquake Data:** Analyzes past earthquakes to predict the frequency, magnitude, and effects of future seismic events.
- **Tectonic Plate Analysis:** Studies the movement of tectonic plates to identify regions with higher seismic risk.
- **Soil Liquefaction Potential:** Assesses the risk of soil liquefaction, which can occur during an earthquake in saturated soils, leading to ground failure.
- **Seismological Networks:** Networks of seismic stations used to detect and monitor earthquake activity in real time, contributing to risk assessment.
- **Risk Mapping:** Combines hazard data with vulnerability information to create maps showing areas at high risk of damage.

II. Principles of Earthquake Engineering

- **Seismic Hazard Assessment:** Understanding the seismic environment, including ground motion characteristics, fault lines, and historical earthquake data, to guide design.
- **Structural Strength and Stiffness:** Ensuring that structures have sufficient strength and rigidity to resist the forces of an earthquake without failing. This includes using appropriate materials and construction techniques.
- **Ductility and Energy Dissipation:** Designing structures to be ductile (able to deform without collapsing) and to dissipate energy during seismic events. This reduces the damage to the structure.
- **Load Distribution:** Ensuring that seismic forces are efficiently distributed across the structure to avoid localized failures, particularly in high-rise buildings and bridges.
- **Lateral Force Resistance:** Earthquakes generate horizontal forces, so it is essential to design for lateral load resistance. This includes using shear walls, bracing systems, and moment-resisting frames.

Load Distribution During Earthquakes

During an earthquake, seismic forces act on a structure in various directions, and how these forces are distributed throughout the building is crucial for its stability and safety. The distribution of loads during an earthquake primarily involves horizontal forces due to ground motion. Here's how load distribution works:

- **Ground Motion and Horizontal Forces:** When an earthquake occurs, the ground shifts horizontally, creating lateral forces that push against the building. These forces are distributed depending on the building's design and configuration.
- **Rigid vs. Flexible Structures:** Rigid buildings tend to transmit lateral forces evenly across their height, while more flexible structures (e.g., taller buildings) may experience uneven distribution of seismic forces. The upper floors of a tall building can experience greater lateral displacement than the lower floors, especially if the building is not properly designed.
- **Load Path:** Seismic forces are transmitted through the building via a load path. This begins at the point where the forces first act (typically the building's upper floors or roof) and travels down through columns, beams, and walls to the foundation. It is crucial to ensure that these load paths are continuous and uninterrupted to prevent failure.

III. Earthquake-Induced Forces on Structures

Earthquake-induced forces on structures are dynamic forces generated by the motion of the ground during an earthquake. These forces affect buildings and infrastructure, and understanding them is critical for designing structures that can withstand seismic events

1. Lateral Forces (Horizontal Forces)

- Earthquakes generate horizontal ground motion, which produces lateral forces that act on the structure. These forces are primarily responsible for causing buildings to sway during an earthquake.
- The magnitude of lateral forces depends on factors such as the building's mass, height, the intensity of ground motion, and the location of the structure relative to the epicenter.

2. Vertical Forces (Gravitational Forces)

- While most earthquake-induced forces are horizontal, vertical forces also play a role. Ground motion can cause temporary vertical accelerations that impact the building's load distribution.
- These vertical forces may alter the weight distribution across the building, especially during significant shaking.

3. Inertial Forces

- When an earthquake shakes the ground, the structure resists this motion due to its inertia. The resulting inertial forces are proportional to the building's mass and the acceleration caused by the earthquake.
- Inertial forces act in the direction of the shaking, causing stress on the structure, particularly on higher floors where movement can be more pronounced.

4. Torsional Forces

- Torsional forces arise when the earthquake's motion causes a twisting or rotational effect in buildings that are not symmetrically designed.
- These forces can cause additional strain on columns, beams, and foundation elements, leading to localized damage if not properly mitigated.
- Asymmetrical or irregular building shapes, such as L-shaped or T-shaped buildings, are more prone to torsional effects during earthquakes.

5. Shear Forces

- Shear forces occur when horizontal motion causes adjacent parts of the structure to move in different directions, generating internal stresses.
- These forces are particularly critical in the structural elements like shear walls, columns, and floors, and can cause material failure if the shear resistance is not adequate.

IV Role of Materials and Design in Earthquake Safety

- **Ductility and Strength:** Materials like steel and reinforced concrete are preferred for their flexibility (ductility) and strength, allowing buildings to absorb and withstand seismic forces.
- **Concrete and Steel:** Reinforced concrete and steel frames are used to resist lateral forces, providing strength and flexibility, especially in tall buildings.
- **Wood:** Lightweight and flexible, wood is effective in low-rise buildings, absorbing seismic energy through bending.
- **Seismic Isolation:** Base isolators decouple buildings from ground motion, reducing seismic impact by allowing controlled movement.
- **Energy Dissipation:** Dampers (viscous, friction) absorb seismic energy, reducing building sway and protecting structural integrity.
- **Symmetry and Regularity:** Symmetrical designs prevent torsional motion during an earthquake, ensuring more stable load distribution.

Innovative Structural Designs

Innovative structural designs enhance earthquake resilience through advanced materials and techniques:

- **Base Isolation:** Uses isolators (e.g., rubber bearings) to decouple buildings from ground motion, reducing seismic impact.
- **Tuned Mass Dampers:** Installed in tall buildings to reduce sway by counteracting motion with a large mass.
- **Shape Memory Alloys (SMAs):** Materials that return to their original shape after deformation, improving recovery and resistance.

- **Energy Dissipation Devices:** Viscous, friction, and hysteretic dampers absorb seismic energy, reducing vibrations.
- **Adaptive Structures:** Active control systems dynamically adjust building stiffness and damping based on seismic activity.
- **Hybrid Structural Systems:** Combines steel and concrete for improved flexibility, strength, and energy dissipation.
- **Seismic Bracing Systems:** Cross-bracing or v-bracing enhances lateral support and prevents deformation.
- **Cantilevered and Modular Designs:** Pre-fabricated components and cantilevered structures improve adaptability and force distribution.

V Technological Advancements in Earthquake Engineering

Technological advancements in earthquake engineering have significantly improved the ability to design and construct buildings and infrastructure that can withstand seismic events. Some key advancements include:

Base Isolation Technology

- Base isolators, such as lead-rubber bearings and elastomeric bearings, decouple buildings from ground motion, reducing seismic forces transmitted to the structure. This technology is increasingly used in both new constructions and retrofitting of existing buildings.

Seismic Sensors and Monitoring Systems

- Seismic sensors and real-time monitoring systems provide immediate data on ground motion and building response. These technologies allow engineers to monitor the performance of structures during an earthquake and adapt safety measures in real time.

Smart Structures

- Active control systems and adaptive damping devices use sensors and actuators to adjust a building's stiffness, damping, and energy dissipation in response to seismic motion. These systems can dynamically control a structure's behavior to minimize damage.

Computer Modeling and Simulation

- Advanced finite element modeling (FEM) and structural simulation software enable engineers to analyze how buildings respond to different earthquake scenarios. These tools help optimize designs and predict structural performance under seismic loading.

Shake Tables and Testing Technologies

- Shake tables simulate ground motion in controlled environments, allowing engineers to test building models or structural components for earthquake resistance. This helps in refining designs before actual construction.

VI Challenges in Earthquake Engineering

Earthquake engineering faces several challenges that need to be addressed to ensure safer buildings and infrastructure in earthquake-prone regions. These challenges include:

Unpredictability of Earthquakes

- Earthquakes are inherently unpredictable in terms of timing, magnitude, and location. This makes it difficult to design structures that can withstand every possible scenario, as engineers must rely on probabilistic seismic hazard assessments that are subject to uncertainty.

Ground Motion Variability

- Ground motion during an earthquake varies greatly depending on factors such as distance from the epicenter, local soil conditions, and topography. Accurately predicting how seismic waves will affect a specific building site remains a significant challenge.

Soil-Structure Interaction

- The interaction between the building and the underlying soil can affect the structure's behavior during an earthquake. Soil conditions, such as liquefaction or soil amplification, can lead to unpredictable settlement or tilting, making it difficult to design foundations that are universally effective.

Retrofit of Older Buildings

- Many older buildings were not designed with modern seismic considerations in mind. Retrofitting these buildings to meet current seismic standards can be expensive and technically challenging, often requiring innovative solutions that do not compromise the building's functionality.

Cost and Budget Constraints

- Seismic-resistant design and construction often require higher costs due to the use of advanced materials, technologies, and complex design solutions. Balancing safety with budget constraints, especially in developing countries or areas with limited resources, presents a major challenge.

VII Future Directions and Innovations in Earthquake Engineering

1. Smart and Responsive Buildings

- **Active and Adaptive Control Systems:** Future buildings may incorporate smart materials and dynamic control systems that adjust their stiffness, damping, and energy dissipation in real-time, responding to seismic forces as they occur. These systems could allow buildings to change their

structural properties during an earthquake to reduce damage.

- **Self-Healing Materials:** Materials that can automatically repair cracks or damage after an earthquake are being developed. These self-healing materials would help reduce long-term repair costs and maintain structural integrity.

2. Integration of Artificial Intelligence (AI) and Machine Learning

- **Predictive Modeling and Risk Assessment:** AI and machine learning algorithms will play a pivotal role in predicting seismic events and analyzing building behavior during earthquakes. These technologies can optimize designs, enhance early warning systems, and improve damage assessment.
- **Automated Structural Monitoring:** AI-powered sensors embedded in buildings could monitor structural health continuously, detecting micro-damages and sending alerts for necessary repairs before issues escalate.

3. Advanced Seismic Simulation and Virtual Reality (VR)

- **Real-time Simulation:** Advances in real-time seismic simulation and virtual reality will allow engineers and architects to visualize and test how buildings behave under various seismic conditions. This will improve design and help with real-time emergency response planning.
- **Virtual Earthquake Testing:** VR can simulate earthquake scenarios to test building performance and train architects and engineers without the need for physical prototypes.

4. Seismic Isolators and Base Isolation Innovations

- **More Efficient Base Isolators:** New materials and designs for base isolators could offer even better performance in reducing seismic forces, making them more affordable and effective for a wider range of buildings, from residential to large infrastructure.
- **Active Isolation Systems:** In the future, active base isolators that use sensors and actuators to adjust their behavior based on real-time seismic data could become commonplace, improving overall building stability.

5. Sustainability and Green Building Practices

- **Eco-friendly Seismic Design:** Innovations in sustainable materials, such as low-carbon concrete and recycled steel, will reduce the environmental impact of seismic-resistant construction while enhancing earthquake resilience.
- **Energy-efficient Earthquake Systems:** The development of energy-efficient damping systems that not only reduce seismic forces but also contribute to energy conservation is expected to play a significant role in future earthquake-resistant designs.

VIII Case studies on earthquake engineering

1.1995 Kobe Earthquake, Japan

Japan improved base isolation, seismic codes, and introduced real-time monitoring to reduce future earthquake damage.

2. 1999 Izmit Earthquake, Turkey

Post-earthquake reforms led to stronger seismic retrofitting, steel bracing, and improved understanding of soil-structure interaction.

3. 2011 Tōhoku Earthquake, Japan

Japan advanced tsunami-resistant design, base isolators, and early warning systems for better protection in future quakes.

4. 2010 Haiti Earthquake

Highlighted the need for reinforced concrete and seismic-resistant construction in developing countries, with training programs for engineers.

5. 2008 Sichuan Earthquake, China

China focused on seismic retrofitting, early warning systems, and improving building codes for vulnerable regions.

6. 1994 Northridge Earthquake, USA

Led to base isolation, steel bracing, and damping systems to reduce building damage and sway during earthquakes.

7. 2001 Gujarat Earthquake, India

India introduced seismic risk management programs, building codes, and retrofitting efforts in earthquake-prone areas.

8. 2016 Kumamoto Earthquake, Japan

Japan applied base isolators to protect cultural heritage and used sensor data for real-time earthquake damage assessment.

9. 2003 Bam Earthquake, Iran

Emphasized reinforced masonry and retrofitting of traditional buildings to improve earthquake resistance in historic areas.

IX Experimental Setup for Damping System Optimization

Structure Design

- Construct small-scale structural models (e.g., single-story or multi-story frames).
- Use materials like aluminum or steel for durability and repeatability.
- Ensure all models are identical except for the damping system configuration.

Damping Systems

- Select multiple damping systems to test, such as:
- Viscous Dampers: Filled with fluid to dissipate energy.
- Tuned Mass Dampers (TMDs): Weights attached via springs to counteract vibrations.
- Friction Dampers: Relying on friction between surfaces to dissipate energy.
- Hybrid Dampers: Combine two or more damping techniques.

Shake Table

- Use a programmable shake table capable of simulating earthquake motions at various frequencies and amplitudes.
- Calibrate the shake table to generate ground motion similar to real seismic events.

Instrumentation

- Equip models with the following sensors:
- Accelerometers: Measure vibration and acceleration.
- Displacement Sensors: Monitor relative movements between levels or at key points.

Testing Procedure

- Secure the model to the shake table.
- Simulate seismic activity at different frequencies and amplitudes.
- Record structural responses for each damping system under identical test conditions.
- Repeat tests for varying levels of seismic intensity.

Data Collection and Analysis

- Analyze sensor data to compare:
- Maximum displacement and acceleration.
- Energy dissipation efficiency.
- Structural stability improvements.
- Identify trends in system performance under different seismic conditions.

Visualization

- Use software to create plots of displacement vs. time, energy dissipation vs. frequency, and other key metrics.
- Highlight differences between the tested damping systems.

Safety Considerations

- Secure all connections to prevent damage to equipment during high-intensity shaking.

- Test within the operational limits of the shake table and damping systems

Category	Result	Value
Seismic Hazard Assessment	Peak Ground Acceleration (PGA)	0.3g
Structural Analysis	Maximum Base Shear	500 kN
Damping Systems	Damping Ratio	5%
Material Strength	Concrete Compressive Strength (f _c)	40 MPa

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