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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

«يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا

الْعِلْمَ دَرَجَاتٍ»

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Dedication

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Marwa BAKHOUCHE

Abstract

Seismic vulnerability remains a critical challenge for reinforced concrete (RC) structures, particularly in seismically active regions such as Algeria. The devastating impacts of past earthquakes, including the El Asnam (1980) and Boumerdès (2003) earthquakes, have exposed significant deficiencies in the design, assessment, and rehabilitation of existing RC buildings. While the Algerian Seismic Code (RPA 99/2003 and RPA 2024) provides seismic design guidelines, it lacks a robust framework for post-rehabilitation evaluation, leading to uncertainties in structural safety and performance after retrofitting. This research develops a comprehensive Algeria-specific seismic assessment framework, integrating performance-based seismic design (PBSD), advanced numerical modeling, and modern rehabilitation techniques to enhance the seismic resilience of existing RC structures. Utilizing ETABS-based numerical simulations, the study evaluates the efficiency of steel bracing systems, fiber-reinforced polymers (FRPs), shape-memory alloys (SMAs), and energy dissipation devices in strengthening RC buildings against seismic forces. The proposed framework is validated through real-world case studies, including healthcare and residential infrastructure in Algeria's high-risk seismic zones. A comparative analysis with international seismic codes (Eurocode 8, ASCE/SEI 41, ACI 318) highlights critical gaps in Algeria's current seismic regulations, advocating for the adoption of advanced assessment techniques, nonlinear dynamic analysis, and post-rehabilitation evaluation criteria. Furthermore, this research examines the implications of RPA 2024, offering insights into how Algeria's seismic regulations can evolve to incorporate modern structural engineering innovations.

The findings contribute significantly to the scientific and engineering community, bridging the gap between global advancements and Algeria's specific seismic challenges. This study provides engineers and policymakers with a scientifically rigorous yet practically feasible tool for seismic assessment and sets a foundation for future research on experimental shake table testing and AI-driven seismic risk assessment.

Keywords: *Rehabilitation, Reinforced Concrete, ETABS, RPA, Seismic Assessment.*

Résumé

La vulnérabilité sismique demeure un défi majeur pour les structures en béton armé (BA), en particulier dans les zones sismiquement actives comme l'Algérie. Les impacts dévastateurs des séismes passés, tels que ceux d'El Asnam (1980) et de Boumerdès (2003), ont révélé d'importantes lacunes dans la conception, l'évaluation et la réhabilitation des bâtiments existants en BA. Bien que le Code Sismique Algérien (RPA 99/2003 et RPA 2024) fournisse des directives de conception parasismique, il existe un besoin d'un cadre robuste pour l'évaluation post-réhabilitation, entraînant des incertitudes quant à la sécurité et aux performances structurelles après renforcement. Cette recherche développe un cadre d'évaluation sismique spécifique à l'Algérie, intégrant la conception parasismique basée sur la performance (PBSD), la modélisation numérique avancée et des techniques de réhabilitation modernes pour améliorer la résilience sismique des structures en BA existantes. À l'aide de simulations numériques via ETABS, l'étude évalue l'efficacité des systèmes de contreventement en acier, des polymères renforcés de fibres (PRF), des alliages à mémoire de forme (AMF) et des dispositifs de dissipation d'énergie dans le renforcement des bâtiments en BA contre les forces sismiques. Le cadre proposé est validé par des études de cas réels, incluant des infrastructures sanitaires et résidentielles situées dans les zones à haut risque sismique en Algérie. Une analyse comparative avec les normes internationales (Eurocode 8, ASCE/SEI 41, ACI 318) met en lumière les lacunes critiques des réglementations algériennes actuelles, plaidant pour l'adoption de techniques d'évaluation avancées, d'analyse dynamique non linéaire et de critères d'évaluation post-réhabilitation. De plus, cette recherche examine les implications du RPA 2024, proposant des pistes pour moderniser les réglementations sismiques algériennes en intégrant des innovations récentes en ingénierie structurelle. Les résultats contribuent significativement aux communautés scientifiques et techniques, en rapprochant les avancées mondiales des défis sismiques spécifiques à l'Algérie. Cette étude offre aux ingénieurs et décideurs un outil rigoureux et réalisable pour l'évaluation sismique, et pose les bases de futures recherches sur les essais expérimentaux sur table vibrante et l'évaluation des risques sismiques pilotée par l'IA.

Mots-clés : *Réhabilitation, Béton armé, ETABS, RPA, Évaluation Sismique.*

ملخص

لا يزال الضعف الزلزالي تحديًا جوهريًا للمنشآت الخرسانية المسلحة، لا سيما في المناطق عالية النشاط الزلزالي مثل الجزائر. حيث كشفت الآثار المدمرة للزلازل التاريخية، مثل زلزال الأبنام (1980) وبومرداس (2003)، عن ثغرات كبيرة في تصميم وتقييم وتأهيل المباني الخرسانية القائمة. وعلى الرغم من أن الكود الزلزالي الجزائري (RPA 99/2003 و RPA 2024) يُقدم معاييرًا للتصميم المضاد للزلازل، إلا أنه يحتاج إلى مزيد من التطوير لتوفير منهجية مُحكمة لتقييم فعالية المنشآت بعد عمليات الترميم، مما يخلق شكوكًا حول سلامتها الهيكلية وأدائها بعد التعزيز. تهدف هذه الدراسة إلى تطوير إطار تقييم زلزالي مُتكيف مع الظروف الجزائرية، يدمج بين مفاهيم التصميم الزلزالي القائم على الأداء (PBSD)، والنمذجة العددية المتقدمة، وتقنيات التأهيل الحديثة لتحسين مرونة المنشآت الخرسانية المسلحة ضد الأحمال الزلزالية. باستخدام نماذج محاكاة رقمية عبر برنامج ETABS، تم تقييم كفاءة أنظمة التعزيز باستخدام الدعامات الفولاذية، والمواد المركبة المُفوّاة بألياف الكربون (FRPs)، وسبائك الذاكرة الشكلية (SMAs)، وأجهزة امتصاص الطاقة في تحسين مقاومة المباني للقوى الزلزالية. كما تم التحقق من صحة الإطار المُقترح عبر دراسات حالة تطبيقية شملت منشآت حيوية (مستشفيات ومباني سكنية) في مناطق الجزائر عالية الخطورة الزلزالية. كشف تحليل مُقارن مع المعايير الدولية (مثل Eurocode 8 و ASCE/SEI 41 و ACI 318) عن نقاط ضعف جوهريّة في التنظيمات الزلزالية الجزائرية الحالية، ودعا إلى اعتماد تقنيات تقييم متطورة (مثل التحليل الديناميكي غير الخطي) ومعايير دقيقة لتقييم المنشآت بعد التعزيز. بالإضافة إلى ذلك، تستكشف الدراسة التحديات والفرص التي يطرحها كود RPA 2024، وتُقدّم مسارات لتحديث اللوائح الجزائرية لمواكبة الابتكارات العالمية في هندسة الزلازل.

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الكلمات المفتاحية: تأهيل، الخرسانة المسلحة، ETABS، RPA، التقييم الزلزالي .

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List of Abbreviations

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ETABS	Extended Three-Dimensional Analysis of Building Systems
FEMA	Federal Emergency Management Agency
FRP	Fiber-Reinforced Polymer
PBD	Performance-Based Design
PBSD	Performance-Based Seismic Design
PGA	Peak Ground Acceleration
RPA	Règlement Parasismique Algérien (Algerian Seismic Code)
RC	Reinforced Concrete
SDoF	Single Degree of Freedom
SHM	Structural Health Monitoring
SMA	Shape-Memory Alloy
THA	Time-History Analysis
UHPC	Ultra-High-Performance Concrete
NDT	Non-Destructive Testing
IO	Immediate Occupancy
LS	Life Safety
CP	Collapse Prevention

Chapter 1: Introduction

*“Between the cracks of ignorance, curiosity lies
the first stone of understanding.”*

1.1 Background

Natural disasters, particularly earthquakes, represent a significant threat to infrastructure and human life worldwide. Reinforced concrete (RC) structures, owing to their strength, durability, and versatility, are widely used in seismic-prone regions. However, their vulnerability to seismic forces highlights the importance of continuous advancements in their design, assessment, and rehabilitation. In Algeria, located along the Mediterranean seismic belt, the threat posed by earthquakes is particularly severe. Notable seismic events, such as the the *El Asnam earthquake* in 1980 (magnitude 7.3) caused widespread destruction and loss of life, revealing severe vulnerabilities in RC structures, especially those constructed before the introduction of modern seismic codes [1]. This earthquake exposed significant deficiencies, such as inadequate reinforcement detailing and poor energy dissipation mechanisms in many buildings. Similarly, the Boumerdès earthquake of 2003, which registered a magnitude of 6.8 and resulted in over 2,000 fatalities and widespread destruction of infrastructure, emphasizes the urgency of improving the seismic resilience of existing RC structures, many of which were not originally designed to withstand severe seismic loads [2].

Despite the existence of the Algerian Seismic Code RPA 99/2003 [3], which provides guidelines for seismic design; the code is limited in its provisions for the post-rehabilitation assessment of existing RC structures. While it addresses some aspects of seismic design for new structures, it does not sufficiently account for advanced evaluation methods or rehabilitation strategies needed to improve older structures' resilience. This gap in the code's provisions makes it difficult to properly assess the effectiveness of rehabilitation measures, leaving much of the existing infrastructure vulnerable to seismic hazards.

1.2 Motivation for the Study

The seismic vulnerability of reinforced concrete structures in Algeria results from various factors, including the country's rapid urbanization, inconsistent construction practices, and inadequate adherence to modern seismic design principles in older structures. Many buildings were constructed before the introduction of modern seismic codes and thus lack essential reinforcement, energy dissipation mechanisms, and other features that enhance seismic performance. The recurrence of significant seismic events, such as the El Asnam and Boumerdès earthquakes, has exposed these deficiencies, leading to widespread damage and, in many cases, catastrophic structural failure.

Significant advancements have been made in seismic rehabilitation techniques, especially for RC structures. Innovative materials such as fiber-reinforced polymers (FRPs), shape-memory

Chapter 1: Introduction

alloys (SMAs), and base isolation systems have shown remarkable potential in improving the seismic resilience of existing structures. These materials help enhance strength, ductility, and energy dissipation, reducing the likelihood of catastrophic failure during an earthquake. Moreover, advanced evaluation techniques, such as pushover analysis, have proven effective in assessing buildings' structural capacity and behavior under seismic loads. Countries such as Japan, Italy, and the United States have integrated these methods into their seismic assessment frameworks to improve the safety and longevity of their built environment.

However, Algeria's seismic design code, RPA 99/2003, is insufficient when it comes to post-rehabilitation evaluation and the integration of these advanced techniques. The absence of performance-based design (PBD) principles and a lack of standardized methods for evaluating rehabilitated structures limit the country's ability to effectively implement modern seismic assessment strategies. Furthermore, Algeria's unique challenges—such as resource constraints and varying construction quality—require a tailored seismic assessment framework that aligns with local conditions while integrating global best practices.

1.3 Problem Statement

The primary problem addressed by this research is the inadequate post-rehabilitation assessment of RC structures in Algeria. Although RPA 99/2003 provides essential seismic design guidelines, it does not offer comprehensive methods for evaluating the seismic resilience of rehabilitated structures. The lack of performance-based design criteria, advanced assessment tools, and modern retrofitting techniques leaves Algeria's existing infrastructure vulnerable to seismic forces. This problem is particularly pressing for older structures, many of which were not designed with modern seismic risks in mind and require retrofitting to meet current safety standards.

Moreover, while global advancements in seismic rehabilitation methods have proven effective in improving the seismic resilience of RC structures, their adoption in Algeria has been limited. The absence of a comprehensive, Algeria-specific seismic assessment framework that integrates these advanced techniques prevents the full potential of these solutions from being realized. Without addressing these issues, Algeria's infrastructure will remain at risk, and local challenges will continue to hinder the adoption of international best practices.

1.4 Objectives of the Study

The main aim of this thesis is to develop a comprehensive framework for assessing the seismic performance and capacity of reinforced concrete (RC) structures after rehabilitation, explicitly tailored to Algeria's seismic conditions. This framework will integrate modern evaluation

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techniques and rehabilitation methods to improve the resilience of Algeria's infrastructure. The specific objectives of the study are as follows:

- ❖ To develop an Algeria-specific seismic assessment framework incorporating local seismic hazard data, performance-based seismic design principles, and advanced rehabilitation techniques.
- ❖ To evaluate the seismic performance of existing RC structures in Algeria, focusing on their vulnerabilities and the impact of rehabilitation interventions.
- ❖ To explore the feasibility of modern retrofitting techniques, such as fiber-reinforced polymers (FRPs), shape-memory alloys (SMAs), and energy dissipation devices, in enhancing the seismic resilience of Algerian RC structures.
- ❖ To validate the proposed framework through case studies of real-world RC structures, assessing the effectiveness of advanced rehabilitation techniques in improving seismic performance.
- ❖ To assess the impact of recent updates in seismic regulations (RPA 2024) on the proposed framework and suggest necessary modifications for compliance.

1.5 Scope and Limitations

Scope:

This study focuses on reinforced concrete structures located in Algeria's high-seismic-risk zones. It addresses the post-rehabilitation assessment and integrating advanced rehabilitation techniques into a new framework for improving seismic resilience. Key areas of focus include:

- Structural assessment techniques.
- Advanced rehabilitation technologies.
- Performance-based design criteria.

Limitations:

- The generalization of findings may be restricted to RC structures in seismic zones in Algeria.
- The availability of field data for Algerian structures is limited, which may impact the depth of analysis for certain case studies.
- Due to resource constraints, Implementation challenges for advanced methods such as SHM systems may limit their practicality in some areas.

1.6 Research Methodology

The research employs a multi-phase methodology to achieve the objectives:

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- **Literature Review:** A comparative analysis of global seismic codes and Algeria's RPA 99/2003. Exploration of advanced rehabilitation techniques and their application to Algeria's infrastructure.
- **Framework Development:** Formulating an Algeria-specific seismic assessment framework that integrates global best practices, advanced techniques, and performance-based criteria.
- **Numerical Analysis:** Modeling RC structures under seismic loads before and after rehabilitation using ETABS software. The study includes pushover and time-history analysis to evaluate the effectiveness of retrofitting techniques.
- **Case Studies and Validation:** The developed framework is applied to selected RC structures in Algeria, and it is validated through simulation results and real-world case studies.

1.7 Thesis Structure Overview

This thesis is organized into seven chapters, each contributing to the development, validation, and application of the Algeria-specific seismic assessment framework for reinforced concrete (RC) structures after rehabilitation:

- **Chapter 1: *Introduction*** – Provides the context, background, and motivation for the research and outlines the research objectives, scope, and methodology.
- **Chapter 2: *Literature Review*** – Reviews global advancements in seismic assessment and rehabilitation, focusing on RC structures, advanced techniques, and performance-based design. It evaluates the limitations of Algeria's seismic code (RPA 99/2003) compared to international standards.
- **Chapter 3: *Algeria-Specific Seismic Assessment Framework*** – Establishes a seismic assessment framework tailored to Algeria's unique seismic hazards, material constraints, and construction practices.
- **Chapter 4: *Numerical Modeling for Seismic Performance Assessment*** – Presents the use of ETABS software for modeling RC structures before and after rehabilitation, applying linear and nonlinear analysis techniques.
- **Chapter 5: *Case Studies and Framework Validation*** – Validates the proposed framework through real-world and hypothetical case studies, assessing the seismic resilience of various RC structures in Algeria before and after rehabilitation.

Chapter 1: Introduction

- **Chapter 6: *Impact of RPA 2024 on the Seismic Assessment Framework*** – Assesses the implications of the recently introduced RPA 2024 on the developed framework, analyzing changes in seismic hazard classification and rehabilitation provisions.

Chapter 7: *Conclusion* – Summarizes the key findings and contributions of the research, proposing future directions for the study and further refinements in rehabilitation techniques.

Chapter 2: Literature Review

*“Knowledge, like
reinforcement, gains strength through
connection — linking what was known to what
remains to be discovered”*

2.1 Introduction

The seismic assessment and rehabilitation of reinforced concrete (RC) structures is a field shaped by decades of research, innovation, and evolving engineering practices. At its core lies the understanding of how RC structures respond to dynamic seismic forces, which has driven the development of global codes, advanced techniques, and materials. Chapter 2 delves into the existing body of knowledge that underpins this research, aiming to establish a foundation for developing a robust seismic assessment framework tailored to Algeria's unique conditions. Despite significant advancements in seismic rehabilitation worldwide, challenges persist in adapting these methodologies to local contexts. Algeria's seismic code, RPA 99/2003 [3], provides a basic framework for seismic design but lacks comprehensive guidelines for post-rehabilitation assessment. Furthermore, the absence of performance-based design (PBD) principles, advanced evaluation techniques like pushover analysis, and innovative materials limit the code's effectiveness in addressing modern seismic demands.

The ASCE/SEI 41 and Eurocode 8 frameworks globally have set benchmarks for integrating PBD, sustainability, and advanced materials into seismic rehabilitation practices. These frameworks allow for targeted interventions based on the desired structural performance level, such as immediate occupancy or life safety. However, their direct application in Algeria is hindered by gaps in construction practices, material availability, and resource constraints. Adapting these methodologies to Algeria requires a critical analysis of global advancements alongside a deep understanding of local challenges.

This chapter systematically reviews the seismic behavior of RC structures, the principles and limitations of global seismic codes, and state-of-the-art rehabilitation techniques. It highlights the gaps in Algeria's current practices and offers insights into how global knowledge can be adapted to create a practical Algeria-specific framework. The review also explores the role of sustainability and economic feasibility in modern seismic rehabilitation, ensuring that proposed solutions align with global trends and Algeria's resource constraints.

Chapter 2 synthesizes findings from international practices and local challenges, laying the groundwork for identifying critical research gaps and establishing the principles that guide the subsequent development of the Algeria-specific framework.

2.2 Importance of Seismic Performance Assessment

In recent years, performance based-seismic design has become an important tool for earthquake resistant design. In addition, performance and assessment are required for existing buildings whereby only gravity load was considered during design, neglecting lateral and seismic load as

Chapter 2: Literature Review

a whole. Performance assessment of existing buildings should be carried out by considering several steps. First, data from the existing building such as (concrete properties, element connection, and corrosion problem) should be collected and its present condition should be determined. Performance level is commonly identified by considering four levels: *Operational, Immediate occupancy, Life-safety, Near collapse*.

Basically, four analysis methods are available for performance and assessment of the existing buildings: *Linear static, Linear dynamic (Response spectrum or Time-history), Non-linear static (Pushover analysis), Non-linear dynamic (Modal pushover/Incremental Response spectrum or nonlinear time-history)*.

2.2.1 Factors Affecting Seismic Performance Assessment

Many structures have been affected by earthquake occurrences, and the most damaged buildings as a result of these events are those which were constructed without due consideration of earthquake codes. The majority of earthquake-related structural damages occur due to:

- Design and construction material problems.
- Insufficient or inaccurate reinforcement details.
- Non-earthquake conformity, projection in planning and bearing systems.
- Construction errors.
- No consideration given to earthquake specification code of practice.
- Geotechnical or soil conditions and economy effects.

The deficiencies mentioned above are principally the reasons for the damage done to buildings during an earthquake. Each will be discussed and elaborated up in turn.

2.2.1.1. Irregular System of Buildings

The irregularity of buildings can be defined as the absence in the design and construction of the building in the event of undesirable seismic behavior. There are several conditions for the irregularity buildings. They are:

- Irregularity in Plan:* Irregular architectural plans of buildings produce irregularity in building systems. Buildings without symmetry in projection of upper floors have impaired earthquake resistance behavior. There are two irregularities that have a main role in resisting earthquake loads. The first one is torsion irregularity causes increasing shear forces in shear walls, columns, corners. Second one is floor discontinuities which are near the circumference of building floor discontinuous in each floor. Typical irregularity in plan is shown in (Fig 2.1).

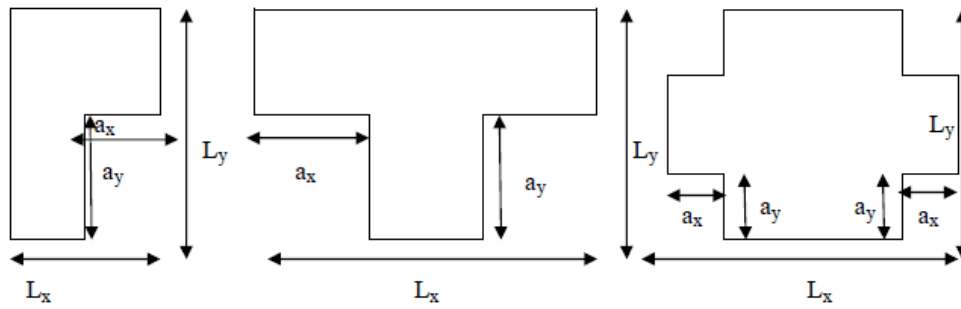
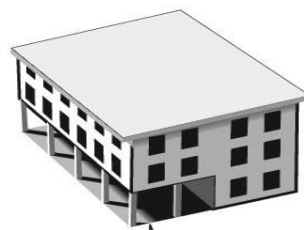


Fig 2.1. Irregularity of Projection in Plan.

B. Irregularity in Elevation: Irregularity in elevation is one of the major damages that exacerbate the risk posed to the building when earthquakes strike. This type of irregularity affects the first story then it will be transferred to the other building floors. The presence of this condition in the first story of the frame structure system (the “ground floor”) can be affected by the zone being free of walls (open floor plan), having stiff non-structural walls in the upper levels, or shear walls being available in the upper story, which do not extend to the foundation but which are disconnected at the second-floor level. Traditional open floors have some disadvantages: *insolubility, inefficiency, and waste*, compared to open floor modern design but also has some of its advantages including economy, hygiene, and pedestrian circulation separation from vehicular traffic.

Soft and weak story irregularity are very common causes of damage in buildings and it is one of the most popular forms of architectural design because of the modern style of architectural configuration being based on five points: *Pilotis (open first floor), the free floor, the free façade, strip windows, roof terrace, and roof gardens*.



“Soft story” buildings have parking or open commercial space on the first floor, making them weaker and more susceptible to collapse in an earthquake.

Fig 2.2. RC building with soft story.

2.2.1.2. Reinforcement Details

Reinforcement details must be endorsed for intermediate moment resisting frames; any lack of reinforcement always causes structural damage or collapse. It is briefly described as follows:

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A. **Beam Details:** The bottom area of the beam at the support face should be able to resist one-third of the hogging moment design when the effected in an inverted direction due to earthquake loads. If the reinforcement of the anchorage length of beam is shorter relative than the development length it may carry tensile stresses and connection is not compacted very well at a junction point (e.g. beam-column junction). To improve this section of structural design you need to add additional bars in the top of the beam, as shown in (Fig 2.3).

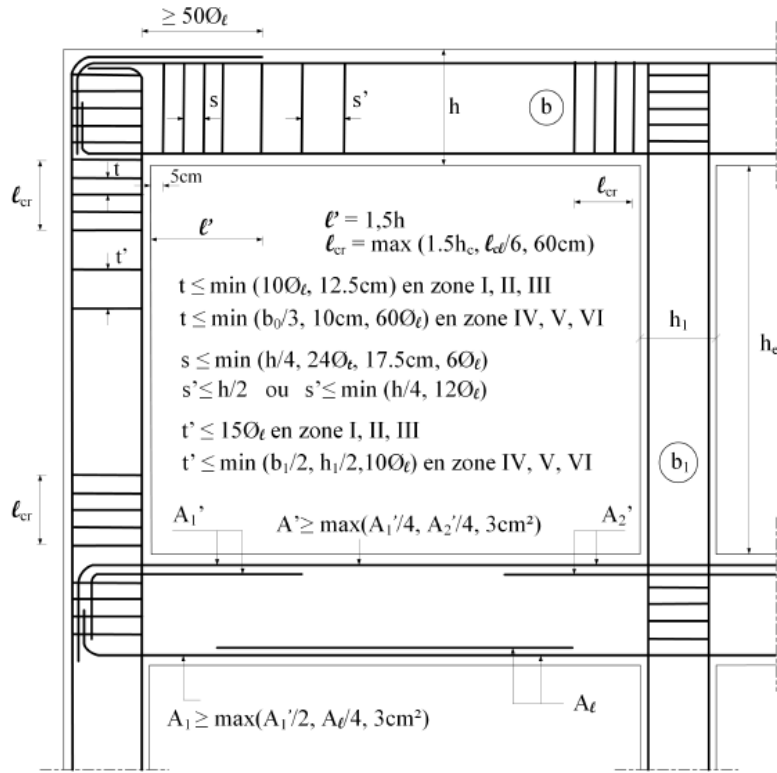


Fig 2.3. Reinforcement detailing of a RC beam (partially adopted from RPA2024) [4].

B. **Column Details:** During earthquake strikes, plastic hinges occur at the end of column and top of the beam at the place that connects them (the beam-column junction). In that location distinguished reversal moment due to the cyclic loading occurs because of high strains by reinforcement. To make it safe during earthquake events columns must be improved by increasing additional shear links and longitudinal reinforcement to get enough durability, structural safety due to energy absorption, as shown in (Fig 2.3).

To improve the absorption of energy to maintain structural safety during severe earthquake depends on ductility and is concerned with:

- Overlapping length joint 50% at story level.

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- Reinforcing bend or hooks and cross ties at the edge of the elements (special hook and special cross ties) used in columns, wall end zones, beam confinement, beam column joints, single and two pieces of hoops, as shown in the fig (Fig 2.5).
- Earthquake resistant stirrups used in columns and beams.

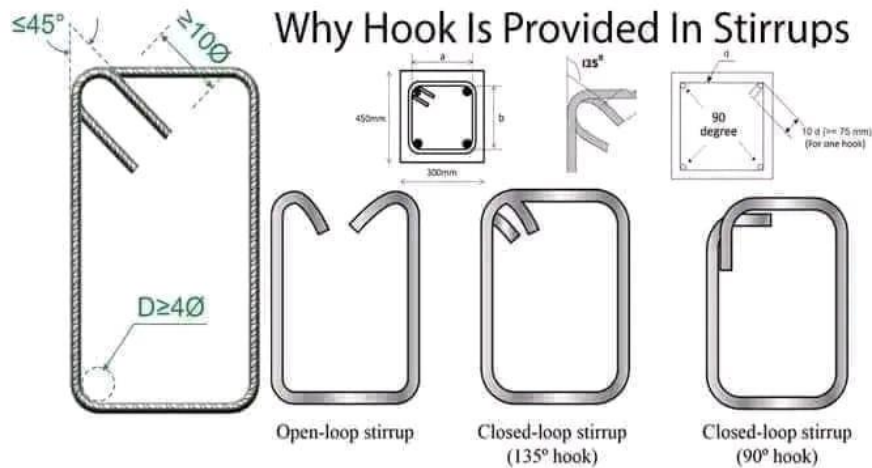


Fig 2.4. Earthquake resistant hooks or bends and cross ties[4].

2.2.1.3. Corrosion Effect

Corrosion means degradation of a metal by an electrochemical reaction with its environment. It has surrounding reinforcement bars until the critical corrosion rate at a specific time then bars cause gap due to corrosion effect. Economic impacts and structural safety concerning the strength and stiffness of RC building are issues arising from corrosion effect. When an earthquake strikes, corrosion causes the reduction of concrete compressive strength, resulting in cracks and less ductility of structural elements.



Fig 2.5. Reinforcement Corrosion.

2.2.1.4. Geotechnical Conditions

The influence of local soil conditions is one of the most dangerous factors effecting the foundation types and whole structure system but it has very less controllable aspects of the real state of soil conditions, depending on seismic wave propagation, epicenter, ground acceleration, amplitude, frequency content, duration, stiffness characteristics. Many types of ground failures directly affect the structures, such as liquefaction, lateral spreading and landslides. Some mitigation of soil is needed before strengthening the building.



Fig 2.6. Structural damage due to liquefaction (Mila City, August 7, 2020).

2.2.1.5. Economy and Cost Conditions

Economic resources must be available for appropriate performance and strengthening enhancement. Sometimes the cost of repair and maintenance of the structure is more than the cost of constructing a new building. In such circumstances it is likely that repair will be neglected, but the following simple balancing equation must be considered before engineering judgment:

$$\text{Cost of strengthening and repair} < \text{Cost of constructing a new building.}$$

2.3 Post-Rehabilitation Assessment Frameworks

Post-rehabilitation assessment frameworks are critical for ensuring the seismic performance of retrofitted reinforced concrete (RC) structures. They provide methodologies for evaluating the effectiveness of rehabilitation techniques and ensuring compliance with safety objectives. This section explores global frameworks such as ASCE/SEI 41 [5], Eurocode 8 [6], and ACI 318 [7], examines Algeria's seismic code RPA 99/2003, and identifies gaps in its post-rehabilitation guidelines.

2.3.1 Global Practices

A. ASCE/SEI 41: Seismic Evaluation and Rehabilitation

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The ASCE/SEI 41 standard provides a performance-based framework for the seismic evaluation and rehabilitation of existing structures, ensuring retrofitted buildings meet safety criteria under seismic loading. It defines performance objectives such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), and uses capacity-demand analysis to assess the adequacy of retrofitted structures during seismic events.

Key Methodologies

- ∞ Linear/Nonlinear Static Analysis (Pushover Analysis): Identifies potential plastic hinge regions and evaluates the capacity of structures under increasing lateral loads.
- ∞ Nonlinear Dynamic Analysis: Uses time-history simulations to capture the behavior of structures during seismic events, providing a detailed performance evaluation.

Rehabilitation Objectives

- ∞ Ensuring collapse prevention under maximum considered earthquake (MCE) scenarios.
- ∞ Achieving life safety during design-level earthquakes.
- ∞ Facilitating immediate occupancy for critical facilities post-earthquake.

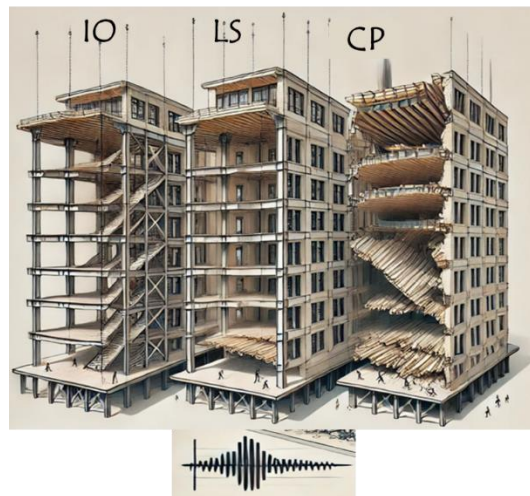


Fig 2.7. Illustration of Performance Objectives in ASCE/SEI 41 [8].

B. Eurocode 8: Guidelines for Retrofitting

The Eurocode 8 framework provides comprehensive guidelines for the seismic evaluation and retrofitting of existing structures. It emphasizes achieving reliability and robustness in retrofitted structures, particularly in high-seismic-risk zones.

Structural Evaluation Methods

- ∞ **Modal Response Spectrum Analysis:** Evaluates the response of structures by considering the contributions of individual vibration modes.

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- ∞ **Incremental Dynamic Analysis:** Uses multiple ground motion records to estimate structural performance across varying intensities of seismic excitation.

Retrofitting Guidelines

- ∞ Strengthening critical elements such as beams, columns, and joints to prevent brittle failure.
- ∞ Enhancing global structural stability by adding shear walls or improving foundation systems.

C. ACI 318: Standards for RC Structures

The ACI 318 code primarily addresses the design and construction of RC structures, including post-rehabilitation assessment methodologies for seismic performance.

Standards for Design and Construction

- ∞ Specifies reinforcement detailing and material properties for new and retrofitted RC structures.
- ∞ Ensures that retrofitted sections can achieve ductility and energy dissipation requirements.

Post-Rehabilitation Evaluation

Requires load-testing of retrofitted components to verify their seismic performance.

Incorporates durability considerations to ensure the long-term functionality of rehabilitated structures.

D. ATC-40: Seismic Evaluation and Retrofit of Concrete Buildings [9]

ATC-40, developed by the Applied Technology Council, is a specialized guideline for evaluating and retrofitting RC structures using nonlinear analysis techniques.

Principles of Evaluation and Retrofit

- ∞ Introduced the Capacity Spectrum Method (CSM) to compare structural capacity with seismic demand.
- ∞ Defines performance levels similar to ASCE/SEI 41, such as IO, LS, and CP, but emphasizes graphical analysis.

Key Methodologies

- ∞ Capacity Spectrum Method: This method combines the structure's capacity curve with the seismic demand spectrum to identify performance points.
- ∞ Nonlinear Static Analysis (Pushover): Evaluates structural behavior under incremental lateral loads.

Applications

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- ∞ Extensively used in regions like California for retrofitting older RC buildings.
- ∞ Suitable for assessing the performance of high-risk structures in urban areas.

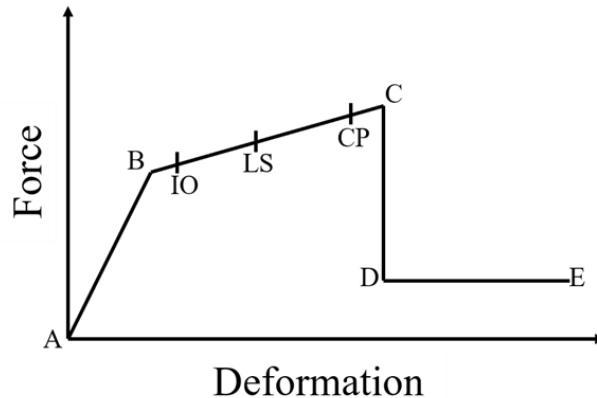


Fig 2.8. Acceptance criteria curve of performance level [10].

E. FEMA Guidelines: NEHRP and FEMA 356 [10]

The FEMA guidelines, particularly FEMA 356 and NEHRP provisions, provide a precursor to ASCE/SEI 41, emphasizing performance-based seismic design and retrofitting.

Principles of Seismic Rehabilitation

- ∞ Defines objectives such as Operational, Life Safety, and Collapse Prevention.
- ∞ Focuses on systematic evaluation to identify critical weaknesses in existing structures.

Key Methodologies

- ∞ Deficiency-Based Evaluation: Identifies vulnerabilities in structural and non-structural components.
- ∞ Dynamic Analysis: Evaluates structural response to simulated earthquake ground motions.

Applications

- ∞ Used across the United States for retrofitting older unreinforced masonry and non-ductile RC structures.
- ∞ Provides foundational guidance for local adoption of modern rehabilitation standards.

Table 2.1. Comparison of Global Seismic Frameworks.

Framework	Focus	Key Methodologies	Applications
ASCE/SEI 41	Performance-based evaluation and design	Nonlinear static and dynamic analysis	Retrofitting critical facilities

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Eurocode 8	Structural robustness in seismic zones	Modal response, incremental dynamic analysis	Public buildings in Europe
ACI 318	Standards for RC design and construction	Reinforcement detailing, ductility provisions	RC structures in the Americas
ATC-40	Capacity spectrum methods	Nonlinear static analysis, capacity-demand	High-risk seismic zones like California
FEMA 356	Prestandard for seismic rehabilitation	Performance-based seismic design	Older masonry and RC buildings in the US

2.3.2 Overview of Algeria's Seismic Code (RPA 99/2003)

The Algerian Seismic Code RPA 99/2003 is a comprehensive framework to ensure the seismic safety of structures in Algeria. Developed in response to major earthquakes, the code has undergone revisions to address emerging challenges and incorporate lessons from seismic events, such as the El Asnam earthquake (1980) and the Boumerdes earthquake (2003). Despite its contributions, RPA 99/2003 has notable limitations in the domain of post-rehabilitation assessment, particularly when compared with advanced international standards like ASCE/SEI 41 and Eurocode 8.

2.3.2.1 Historical Context and Evolution

A. Origins and Early Development:

Algeria's seismic code, the "Réglement Parasismique Algérien" (RPA), originated after the devastating El Asnam earthquake of 1980, which caused significant destruction and loss of life. This 7.3 magnitude earthquake exposed severe deficiencies in reinforced concrete (RC) structures, primarily due to inadequate seismic design, poor reinforcement detailing, and substandard construction practices [11] [12]. In response, the Algerian government prioritized developing a seismic code to mitigate future risks. The early RPA versions, introduced in the 1980s, focused on designing new structures with force-based methods but lacked provisions for retrofitting existing buildings, a gap highlighted by later seismic events [13].

The RPA aimed to align with international standards while addressing Algeria's unique seismic challenges. Early versions laid the groundwork for the comprehensive RPA 99/2003, which incorporated updated seismic hazard zoning and advanced design

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requirements. This evolution underscores the importance of continuous improvement in seismic regulations to address both new constructions and existing vulnerabilities.

B. Revision Post-Boumerdes Earthquake (2003):

The Boumerdes earthquake of 2003 (magnitude 6.8) revealed critical deficiencies in Algeria's seismic infrastructure, particularly in older buildings that lacked adequate reinforcement, ductility, and lateral force resistance, leading to widespread damage and over 2,000 fatalities [14].

In response, the RPA 99/2003 seismic code was revised to improve the resilience of new constructions. Key updates included revised seismic hazard zoning based on updated geological data, enhanced provisions for ductility and lateral resistance, and improved reinforcement detailing in critical areas like beam-column joints. The code also emphasized the integration of shear walls and braced frames for better stability under seismic loads. These revisions aligned Algeria's seismic regulations with international standards but still faced challenges in addressing the vulnerabilities of older, non-compliant structures in high-risk seismic zones.

C. Geographical Seismic Hazard Zoning:

The RPA 99/2003 seismic code divides Algeria into four seismic hazard zones—Zone 0, I, IIa/b, and III—to address varying seismic risks. These zones are based on historical seismicity, tectonic activity, and soil conditions, ensuring that structural designs are tailored to regional risks:

- **Zone I:** Low seismic risk with minimal strong ground motion, requiring standard construction practices with less seismic reinforcement.
- **Zone IIa/b:** Moderate seismic risk, necessitating enhanced design to accommodate potential ground shaking.
- **Zone III:** High seismic risk, with strict design measures to ensure ductility, lateral force resistance, and energy dissipation in areas with active fault lines.

This zoning is integral to Algeria's seismic mitigation strategy, particularly in high-risk areas like the Tell Atlas fault system, ensuring that structures can withstand higher seismic forces and mitigate risks based on lessons from past events such as the El Asnam (1980) and Boumerdes (2003) earthquakes [15].

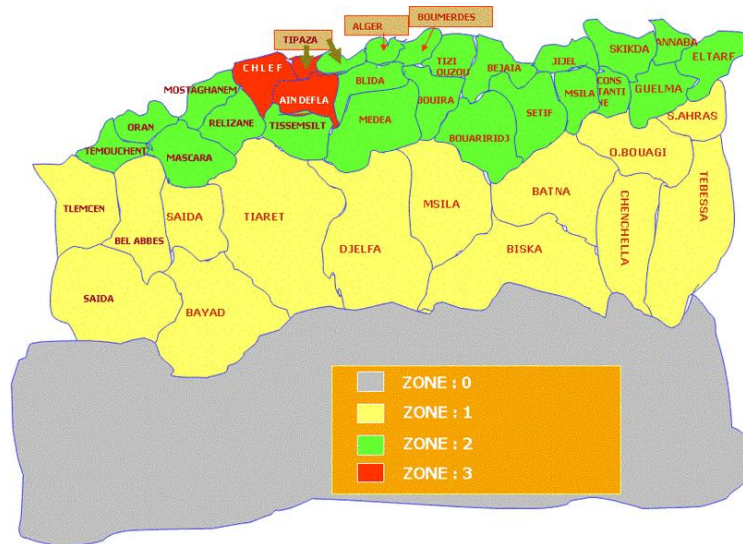


Fig 2.9. Algeria's Seismic Hazard Zoning Map [16] [3].

2.3.2.2 Post-Rehabilitation Guidelines and Limitations

The RPA 99/2003 seismic code primarily focuses on the seismic design of new structures, with limited provisions for retrofitting or post-rehabilitation assessment of existing reinforced concrete (RC) buildings. This section outlines the general recommendations provided by the code, highlights its significant limitations in addressing retrofitting practices, and compares its approach to international standards.

A. Existing Guidelines

The retrofitting provisions in RPA 99/2003 are minimal and conceptual, aimed at enhancing the stiffness and strength of existing structures. Key recommendations include:

∞ Basic Strengthening Measures:

- **Shear Walls:** Suggested to improve lateral stability and reduce inter-story drifts, especially in high-risk zones like Zone III.
- **Jacketing of Structural Members:** Reinforced concrete or steel jacketing enhances load-carrying capacity and ductility, particularly for under-confined columns and beams.
- **Connection Enhancements:** Strengthening beam-column joints with additional reinforcement or materials to improve load transfer during seismic events.

∞ Simplified Assessment Approach:

- The code provides prescriptive guidelines for assessing structural integrity but relies on simplified methods, lacking performance-based techniques to evaluate post-damage or post-rehabilitation capacity.
- These basic measures fail to address modern advancements in structural analysis or complex retrofitting challenges in high-risk seismic zones.

B. Limitations

The limitations of RPA 99/2003 in addressing post-rehabilitation scenarios are significant when compared to international standards like ASCE/SEI 41, Eurocode 8, or FEMA 356.

These limitations include:

- ∞ **Absence of Performance-Based Design Criteria:** Unlike international codes, RPA 99/2003 does not define performance objectives such as Immediate Occupancy (IO), Life Safety (LS), or Collapse Prevention (CP). This makes it difficult to evaluate retrofitted structures under varying seismic scenarios and tailor rehabilitation strategies accordingly.
- ∞ **Lack of Guidance on Advanced Techniques:** The code does not include guidelines for advanced evaluation methods like Pushover Analysis, Nonlinear Dynamic Analysis, or Structural Health Monitoring (SHM), which limit the precision and adaptability of retrofitting, particularly for older or complex buildings.
- ∞ **No Post-Rehabilitation Verification Procedures:** RPA 99/2003 lacks mechanisms for verifying the effectiveness of retrofitting measures, such as Load Testing and Dynamic Simulations, which are commonly used in international frameworks to ensure retrofitted buildings meet safety and performance objectives.

2.3.2.3 Comparison with Global Standards

While the RPA 99/2003 seismic code significantly improves Algeria's seismic resilience, it has notable differences and limitations compared to international standards such as ASCE/SEI 41, Eurocode 8, and ACI 318. This section evaluates the strengths and gaps in RPA 99/2003, focusing on methodologies, performance objectives, retrofitting provisions, and verification procedures.

A. Methodologies: RPA 99/2003 primarily uses force-based design methods, including equivalent static and modal response spectrum analysis. While effective for new structures, these methods are less suited for retrofitted or irregular buildings.

Global Standards: ASCE/SEI 41 and Eurocode 8 incorporate performance-based design (PBD), using nonlinear static (pushover) and dynamic analyses to evaluate structural responses under varying seismic intensities.

Limitations in RPA 99/2003: Force-based design limits its ability to model nonlinear behavior or assess the residual capacity of retrofitted structures, and the absence of

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advanced techniques like time-history or pushover analysis reduces the precision of rehabilitation assessments.

Table 2.2. Comparison of Methodologies.

Standard	Analysis Methodologies	Focus
RPA 99/2003	Force-based, Equivalent Static Analysis	Simplicity for new structures
ASCE/SEI 41	Nonlinear Static, Dynamic Analyses	Advanced retrofitting evaluations
Eurocode 8	Modal Response, Incremental Dynamic Analysis	Comprehensive seismic assessment

B. Performance Objectives: RPA 99/2003 does not define performance objectives for retrofitted or new structures, limiting its ability to evaluate post-rehabilitation performance.

- ∞ **Global Standards:** ASCE/SEI 41 and Eurocode 8 emphasize performance objectives such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), ensuring tailored retrofitting strategies.
- ∞ **Limitations in RPA 99/2003:** The lack of performance objectives prevents engineers from systematically assessing whether retrofitting measures meet the desired safety and operational goals.

C. Retrofitting Provisions: RPA 99/2003 offers general retrofitting recommendations, such as adding shear walls and jacketing columns, but lacks detailed methodologies for advanced techniques.

- ∞ **Global Standards:** ASCE/SEI 41 and Eurocode 8 provide comprehensive retrofitting provisions, including base isolation, energy dissipation devices, and fiber-reinforced polymer (FRP) retrofitting, validated through nonlinear analysis.
- ∞ **Limitations in RPA 99/2003:** Limited focus on advanced techniques, such as shape-memory alloys (SMAs) or structural health monitoring (SHM), and no guidelines for integrating innovative materials into retrofitted structures.

C. Verification Procedures: RPA 99/2003 does not offer detailed guidelines for verifying the effectiveness of retrofitting measures, which creates uncertainty about the safety of rehabilitated structures.

- ∞ **Global Standards:** ASCE/SEI 41 uses load testing and dynamic simulations to verify retrofitted structures, while Eurocode 8 requires validation through incremental dynamic analysis or time-history simulations.
- ∞ **Limitations in RPA 99/2003:** The absence of verification procedures diminishes the reliability of retrofitting measures, especially in high-risk seismic zones like Zone IIIa/b.

2.4 Rehabilitation Techniques and Their Effects

The rehabilitation of RC structures in seismically active regions like Algeria requires the careful selection of techniques to restore and enhance structural performance. This section provides an overview of common rehabilitation methods, with a focus on seismic resilience. Given Algeria's diverse environmental conditions and seismic vulnerabilities, these techniques are evaluated for their suitability within the Algerian context, supporting the development of a robust post-rehabilitation framework in Algeria's seismic code, RPA 99/2003. The following subsections analyze both conventional and advanced rehabilitation techniques, considering their effects on ductility, stiffness, durability, and overall seismic performance.

2.4.1. Conventional Rehabilitation Techniques

Conventional rehabilitation techniques have long been employed to improve the seismic resilience of RC structures. In Algeria, where seismic vulnerability is a major concern, traditional methods such as FRP wrapping, steel jacketing, steel bracing, and shear wall addition form the foundation of seismic retrofitting. These techniques are assessed for their application, effectiveness, and limitations within Algeria's specific seismic context.

2.4.1.1. Fiber Reinforced Polymer (FRP) Wrapping:

FRP wrapping involves applying composite materials, such as carbon or glass fibers embedded in a polymer matrix, around RC elements to enhance axial and flexural strength. This lightweight, high-strength material improves load-bearing capacity without significantly increasing the structure's weight, making it ideal for seismic retrofitting [17].

- ∞ **Impact on Seismic Resilience:** FRP wrapping enhances ductility by providing lateral confinement, allowing structures to deform without failure and absorb seismic energy, reducing brittle failure. Its high strength-to-weight ratio and corrosion resistance are especially beneficial in Algeria's coastal areas. Studies show

that FRP-wrapped columns demonstrate improved ductility and delayed cracking under seismic loads [18][19].

- ∞ **Limitations and Challenges:** In humid environments, such as Algeria's coastal regions, moisture can degrade the adhesive bond between FRP and concrete, causing debonding under cyclic loading. Additionally, uneven application may lead to stiffness inconsistencies, affecting the building's dynamic response. Protective coatings or hybrid techniques combining FRP with other methods may address these issues[20] [21].



Fig 2.10. RC Column with FRP Wrapping for Enhanced Seismic Resilience [8].

2.4.1.2. Steel Jacketing:

Steel jacketing involves enclosing RC elements with welded or bolted steel plates, enhancing axial load-carrying capacity and flexural strength. It is commonly used to rehabilitate columns, beams, and joints exposed to seismic forces [22].

- ∞ **Impact on Seismic Performance:** Steel jacketing increases both ductility and shear strength by confining concrete, improving energy absorption and reducing brittle failure. This technique enhances stability and load distribution during seismic events [23].
- ∞ **Drawbacks:** Steel jacketing adds weight to the structure, which may require further retrofitting to support the additional load. It is also prone to corrosion in humid or coastal environments, limiting its longevity unless protective coatings are applied. The high cost and specialized labor required may also limit its scalability, especially in resource-constrained areas like Algeria [24].



Fig 2.11. Reinforced Concrete Column with Steel Jacket [8].

2.4.1.3. Steel Braces

Steel braces are added to RC frames to increase lateral load resistance, control deflection, and improve seismic resilience. They redistribute seismic forces across the structure, reducing the load on individual elements. Steel braces can be concentric (X, V, inverted V, or K-brace) or eccentric, with each type offering specific advantages depending on the structural needs.

- ∞ **Purpose and Mechanism:** Steel braces provide additional paths for seismic forces, reducing demand on critical components and enhances lateral stiffness, particularly in taller buildings in high-seismic zones, also Absorbs and dissipates seismic energy, minimizing damage to primary structural elements.
- ∞ **Advantages of Steel Braces in Seismic Retrofitting:** Steel braces improve stability and reduce seismic drift, more affordable than advanced techniques like base isolation or energy dissipation devices, can be added with minimal disruption to the existing structure, adaptable to various structural configurations.
- ∞ **Limitations and Challenges:** Braces may obstruct windows or doorways, affecting building functionality, susceptible to buckling under compression, and corrosion in humid areas may require maintenance, increases the overall load, potentially impacting foundations and other load-bearing elements in older buildings.
- ∞ **Applicability in Algeria:**

Steel braces are well-suited for Algeria's seismic zones, offering an effective balance between cost and performance. They align with local construction practices and material availability, making them a viable solution for seismic retrofitting.



Fig 2.12. RC Building with Added Steel Braces for Enhanced Seismic Load Path and Stiffness [8].

2.4.1.4. Shear Wall Addition

Shear walls are vertical structural elements designed to resist lateral seismic forces. They are integrated into a building's framework to improve both stiffness and stability [25].

- ∞ **Effect on Building Dynamics:** Adding shear walls increases lateral stiffness and reduces inter-story drift during seismic events. However, it may increase seismic forces if not carefully designed, as this added stiffness can alter the building's dynamic characteristics. Proper positioning is critical to avoid amplifying vibrational modes [26].
- ∞ **Applicability in Algeria:** Shear walls are a practical and widely used technique for enhancing lateral load resistance, especially in high-seismic-risk areas like northern Algeria. Although their installation may be disruptive and require significant structural modifications, they remain one of the most effective methods for improving seismic resilience [27].



Fig 2.13. Reinforced Concrete Building with Added Shear Walls [8].

2.4.2 Advanced Rehabilitation Techniques

Advanced rehabilitation techniques offer innovative solutions for enhancing the seismic resilience of reinforced concrete (RC) structures in high-risk areas. This section explores methods such as base isolation systems, energy dissipation devices, and advanced materials, focusing on their potential impact on Algeria's infrastructure. While these techniques provide promising results in mitigating seismic forces and enhancing structural stability, they come with unique challenges related to cost, technical expertise, and implementation feasibility in Algeria.

2.4.2.1. Base Isolation Systems

Base isolation systems work by decoupling a building's superstructure from ground motion during an earthquake. Flexible bearings or isolators are installed between the foundation and the superstructure, absorbing and dissipating seismic energy. This decoupling significantly reduces acceleration and deformation demands, enhancing resilience in seismic zones [28].

- ∞ **Benefits for Seismic Zones:** Base isolation effectively reduces structural damage and protects occupants during earthquakes. Studies in seismically active regions, such as Japan and New Zealand, have demonstrated that base isolation can reduce lateral forces and inter-story drifts by 50-70% compared to conventional construction [29] [30] [31]. This makes it especially beneficial for buildings housing critical infrastructure like hospitals, schools, and emergency response centers.

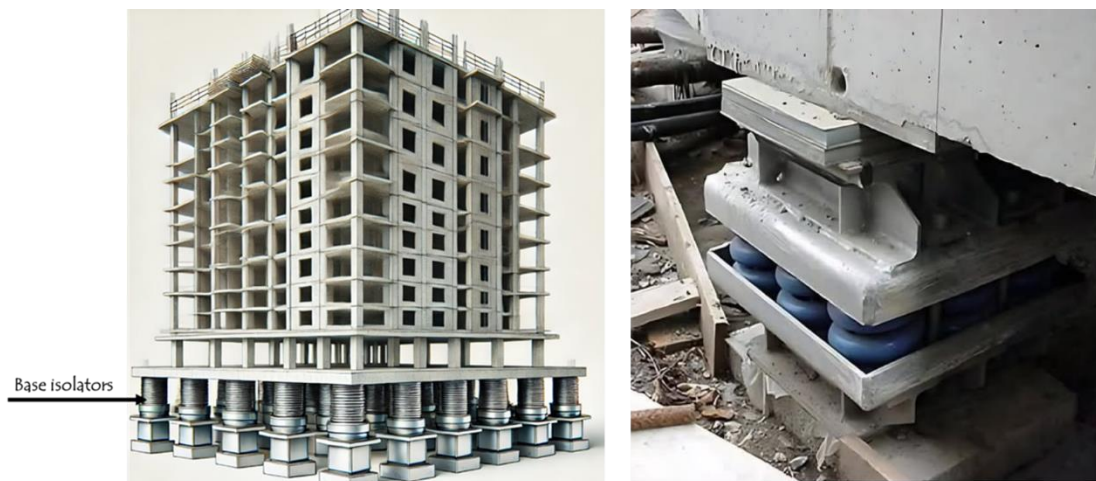


Fig 2.14. Seismic Base Isolation System in Multi-Story RC Building [8].

- ∞ **Challenges and Feasibility in Algeria:** Implementing base isolation in Algeria faces challenges due to the high cost and technical expertise required. While it is feasible for new construction, retrofitting existing buildings is complex and

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expensive. The lack of specialized equipment and trained personnel also complicates its adoption. In the short term, base isolation may be best suited for critical infrastructure, with potential government subsidies or international partnerships to improve accessibility.

2.4.2.2. Energy Dissipation Devices

Energy dissipation devices, including viscous dampers, friction dampers, and tuned mass dampers (TMDs), are designed to absorb and dissipate seismic energy, reducing the amplitude of vibrations. These devices work by converting seismic kinetic energy into heat or other forms of energy.

Table 2.3. Comparison of Energy Dissipation Devices for Seismic Applications.

Dissipation Device	Key Properties	Effectiveness	Typical Applications
Viscous Dampers	Uses fluid viscosity to dissipate energy	High effectiveness in reducing building vibrations and displacements	High-rise buildings, bridges, retrofitted RC structures
Friction Dampers	The energy dissipated through frictional sliding	Effective in controlling lateral displacements	Industrial facilities, buildings in seismic retrofitting
Tuned Mass Dampers (TMDs)	Mass-spring-damper system that counteracts building movement	Best for reducing vibrations in tall buildings	Skyscrapers, towers, and tall commercial buildings

- ∞ **Impact on Structural Performance:** These devices enhance structural resilience by lowering vibration and lateral displacement, decreasing stress on critical components and prolonging the structure's lifespan. Research shows that buildings with dampers experience 40-60% lower displacement and drift during seismic events [32] [33].
- ∞ **Implementation Feasibility in Algeria:** Despite their benefits, the high initial and maintenance costs, along with the need for specialized installation, make energy dissipation devices less feasible for widespread adoption in Algeria. However, they could be prioritized for essential buildings and high-rise structures, where the cost-benefit ratio justifies their use. Partnerships with international seismic technology providers could help mitigate costs.

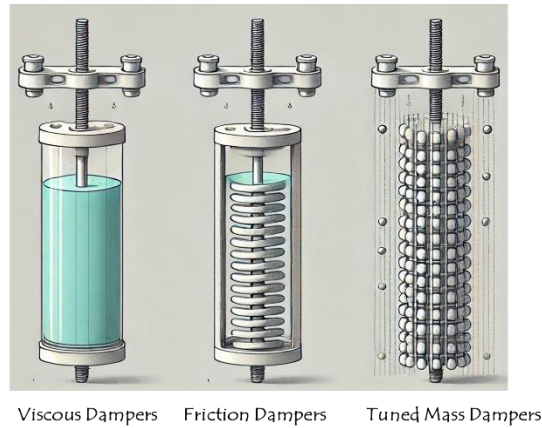


Fig 2.15. Types of Energy Dissipation Devices for Seismic Protection [8].

2.4.2.3. Advanced Materials for Seismic Retrofitting

A. Ultra-High-Performance Concrete (UHPC): UHPC is an advanced composite material characterized by its superior compressive strength, ductility, and durability. These properties make UHPC especially suitable for seismic retrofitting, providing enhanced confinement to RC structures [34]. UHPC's high durability also improves structural resilience in harsh environmental conditions, such as those found in Algeria's coastal and desert regions [35].

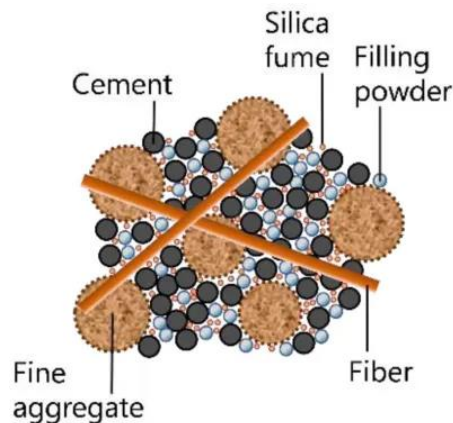


Fig 2.16. Composition of Ultra-high-performance Concrete.

B. Shape Memory Alloys (SMAs): SMAs are metallic materials that return to their original shape after deformation when subjected to temperature changes. In seismic applications, SMAs provide self-centering capabilities, reducing residual displacements in RC structures after an earthquake [36].

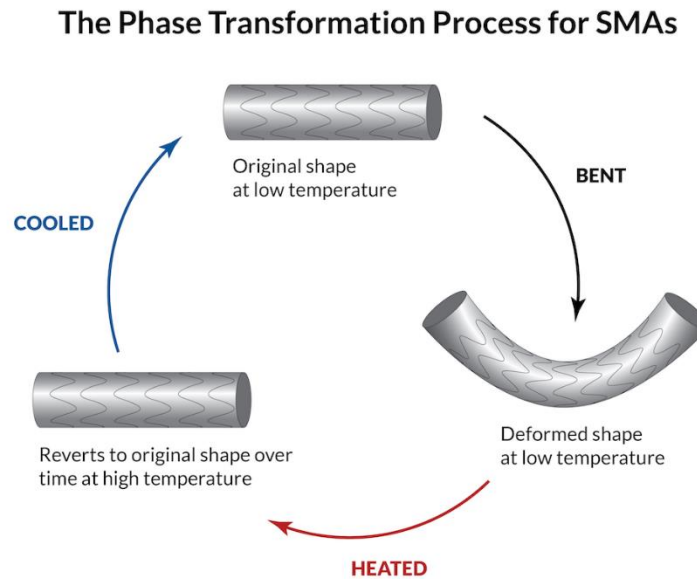


Fig 2.17. The basic phase transformation process in an SMA.

- ∞ **Feasibility and Cost Implications in Algeria:** While advanced materials like UHPC and SMAs show promise, their cost and supply chain challenges limit their widespread use in Algeria. UHPC is more expensive than conventional concrete, and SMAs are costly due to their specialized properties and limited suppliers. Despite these barriers, targeted use in critical infrastructure could enhance resilience in seismic zones. A phased approach, supported by government and international funding, could make these technologies more feasible in the long term.

2.4.2.4. Summary of Advanced Techniques for Algerian Context

In summary, advanced rehabilitation techniques offer considerable promise for enhancing seismic resilience in Algeria's RC structures. While each method—base isolation, energy dissipation devices, and advanced materials—presents challenges in terms of cost, technical expertise, and infrastructure compatibility, their strategic implementation could transform Algeria's approach to seismic rehabilitation. A phased adoption strategy, potentially funded by government initiatives or international aid, could allow for gradual integration of these techniques into the Algerian construction landscape, ultimately contributing to safer, more resilient infrastructure.

2.5 Evaluation and Monitoring Methods

This section presents the evaluation methods used to assess the effectiveness of seismic rehabilitation techniques. These methods allow engineers to design, validate, and continuously monitor retrofitted structures, ensuring they meet safety and performance

objectives during and after seismic events. Key evaluation techniques, such as pushover analysis and nonlinear time history analysis (NLTHA), assess structural response.

2.5.1. Pushover Analysis

Pushover analysis is a nonlinear static method that evaluates a structure's capacity to resist seismic forces by applying incremental lateral loads. It simulates the transition from elastic behavior to plastic deformation and eventual failure, helping identify weak zones and optimize rehabilitation strategies.

- ∞ **Applications:** Pushover analysis locates regions likely to form plastic hinges, such as beam-column joints or shear walls. It generates capacity curves (base shear vs. displacement) to compare seismic demand against structural capacity and evaluates improvements in performance following retrofitting.
- ∞ **Advantages:** This method is easy to implement using structural analysis software like ETABS and SAP2000 and provides insight into the sequence of structural failures during seismic loading.

“Further details and examples of pushover analysis are provided in Chapter 4”.

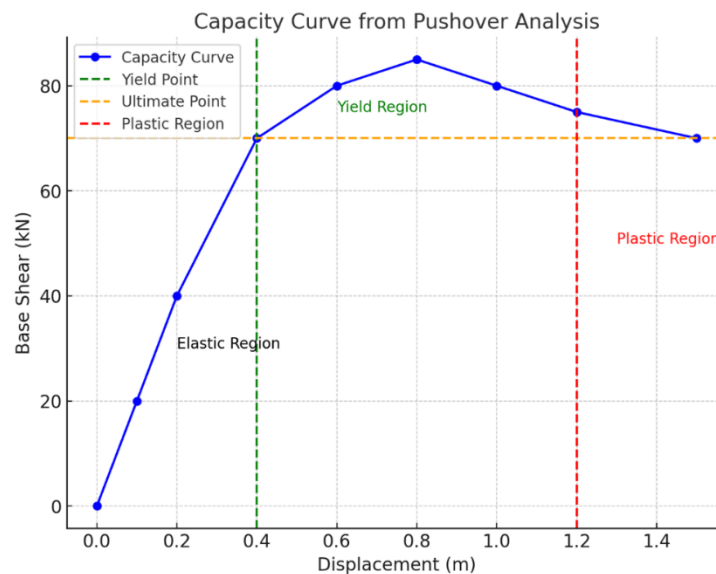


Fig 2.18. Capacity Curve from Pushover Analysis.

2.5.2 Nonlinear Time History Analysis (NLTHA)

NLTHA is a nonlinear dynamic analysis method that assesses a structure's response under real or simulated seismic ground motions. Unlike pushover analysis, it captures the time-dependent behavior of a building, providing a realistic evaluation of structural performance during earthquakes.

- ∞ **Applications:** NLTHA validates rehabilitation techniques, including conventional and advanced techniques, by ensuring they perform effectively under actual seismic

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conditions. It also analyzes dynamic behavior, such as displacement, acceleration, and forces.

- ∞ **Advantages:** NLTHA accurately predicts structural responses under varying seismic intensities and identifies residual deformations and potential failure mechanisms.
- ∞ **Challenges:** It is computationally intensive, requires specialized expertise, and relies on high-quality ground motion data.

“Further details and examples of NLTHA are provided in Chapter 4”.

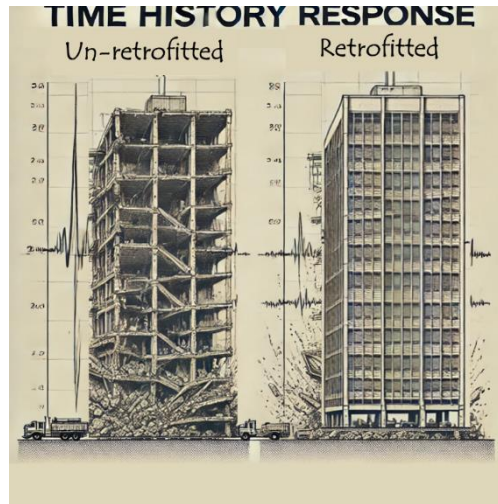


Fig 2.19. Time History Response of un-retrofitted and Retrofitted Buildings [8].

2.5.3 Experimental Validation Techniques

Experimental validation involves physical testing of retrofitted components or scaled models to confirm performance under seismic loads. Common methods include *shake table testing*, which simulates seismic forces on scaled models, and *cyclic load testing*, which evaluates components such as beam-column joints or shear walls under repeated loading.

- ∞ **Applications:** These methods validate advanced materials such as FRPs, SMAs, and UHPC, and provide critical data to refine computational models.
- ∞ **Advantages:** Experimental validation directly measures the effectiveness of rehabilitation techniques and reduces uncertainties associated with numerical simulations.



Fig 2.20. Shake Table Testing Setup [8].

Evaluation methods such as pushover analysis, NLTHA, and experimental validation are essential for ensuring the effectiveness of advanced rehabilitation techniques. Integrating these methods into Algeria's seismic framework would enhance the capacity to evaluate and monitor rehabilitated buildings, ensuring safety and resilience during seismic events.

2.6 Identified Research Gaps

This chapter concludes by evaluating the gaps in Algeria's current seismic rehabilitation and assessment practices, highlighting the limitations of RPA 99/2003, the need for a country-specific framework, and directions for future research. Addressing these gaps is crucial for improving seismic resilience, ensuring cost-effective and sustainable rehabilitation, and aligning practices with international standards.

2.6.1 Gaps in RPA 99/2003

Despite its advancements, RPA 99/2003 faces significant limitations in addressing modern seismic challenges and rehabilitation needs:

2.6.1.1. Lack of Advanced Assessment and Rehabilitation Techniques:

RPA 99/2003 relies primarily on force-based design approaches and provides minimal guidance on advanced nonlinear methods such as pushover analysis and NLTHA, which are essential for evaluating post-rehabilitation performance. The code also offers only general strengthening recommendations, like adding shear walls, without addressing advanced techniques such as base isolation or energy dissipation devices.

2.6.1.2. Minimal Integration Innovative Materials

The code does not include provisions for modern materials, such as fiber-reinforced polymers (FRPs), shape-memory alloys (SMAs), or geopolymer concrete, limiting the adoption of high-performance and sustainable solutions.

2.6.1.3. Absence of Clear Performance-Based Design and Verification Methods

Unlike international standards (e.g., ASCE/SEI 41, Eurocode 8), RPA 99/2003 lacks defined performance objectives such as Immediate Occupancy, Life Safety, and Collapse Prevention for rehabilitated structures. Verification procedures, including load testing and dynamic simulations, are not outlined, restricting the ability to systematically assess rehabilitation outcomes.

2.6.1.4. Need for Algeria-Specific Assessment Framework

Algeria's unique seismic hazards and resource constraints necessitate a tailored framework.

Key considerations include:

- ∞ **Seismic Hazard Variability:** Accounting for diverse risks across Zones 0 to III, including soft-story collapses and weak foundations.
- ∞ **Environmental Conditions:** Addressing impacts of arid and semi-arid climates, such as accelerated concrete degradation and reinforcement corrosion.
- ∞ **Material Availability:** Integrating locally available or recycled materials due to high import costs of advanced materials.
- ∞ **Cultural and Economic Factors:** Local construction practices require specific training and capacity building for effective implementation of advanced techniques.

2.7 Conclusion

This chapter has explored critical seismic rehabilitation and structural assessment aspects through a comprehensive literature review. It examined global best practices, advanced rehabilitation techniques, and the gaps in Algeria's seismic code (RPA 99/2003). The analysis revealed the pressing need for an Algeria-specific assessment framework that integrates advanced technologies, performance-based methodologies, and sustainable rehabilitation strategies tailored to the country's unique seismic and environmental conditions.

Key insights include:

- ∞ The inadequacy of RPA 99/2003 in addressing modern seismic challenges, particularly in post-rehabilitation assessment and the adoption of innovative materials such as FRPs and SMAs.

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- ∞ The significant role of advanced evaluation techniques like pushover analysis, nonlinear time history analysis in ensuring the seismic resilience of retrofitted structures.
- ∞ The critical importance of sustainability in rehabilitation projects, emphasizing the need for local materials, lifecycle cost analysis, and policy frameworks to address Algeria's resource constraints.

These findings highlight the imperative to bridge the gap between global advancements and Algeria's specific needs. By adapting international standards like ASCE/SEI 41 and Eurocode 8, incorporating advanced evaluation and rehabilitation techniques, Algeria can build a robust framework for seismic resilience.

This foundation sets the stage for subsequent chapters, where a tailored Algeria-specific seismic assessment framework will be developed. The forthcoming work will focus on adapting global methodologies to local conditions, integrating innovative technologies, and ensuring cost-effective and environmentally sustainable solutions for rehabilitating Algeria's RC structures. This approach will address the gaps identified and enhance the safety, durability, and long-term resilience of Algeria's infrastructure in seismic-prone regions.

Chapter 3: Algeria-Specific Seismic Assessment Framework

*“In Algeria’s soil, history
and hazard converge — and from their meeting, a new framework is
born....”*

3.1 Introduction

Algeria's vulnerability to seismic activity, stemming from its location along the tectonically active Mediterranean seismic belt, poses significant challenges to the resilience of its reinforced concrete (RC) infrastructure. Historical events such as the Boumerdes earthquake (2003) and the El Asnam earthquake (1980) have highlighted critical deficiencies in structural design and construction practices, underscoring the need for a tailored assessment and rehabilitation framework. While global standards such as ASCE/SEI 41, Eurocode 8, and ACI 318 offer comprehensive seismic evaluation and retrofitting guidance, Algeria's unique seismic, environmental, and resource conditions necessitate a more localized approach.

This chapter aims to establish a seismic assessment framework specifically designed for Algeria, addressing gaps in the current seismic code (RPA 99/2003) and leveraging global best practices. The proposed framework integrates advanced evaluation methods, innovative materials, and sustainable rehabilitation techniques while accounting for local conditions such as material availability, soil behavior, and resource constraints. By defining performance-based criteria, the framework seeks to enhance the resilience and post-rehabilitation performance of RC structures in Algeria's diverse seismic zones.

The chapter begins with an overview of Algeria's seismic profile, focusing on its seismic hazard zones, the historical earthquake performance of RC structures, and the influence of soil-structure interaction. It then details the methodology for designing the framework, including integrating Algeria-specific seismic parameters and establishing key performance indicators. The framework's components are explored in-depth, covering pre-rehabilitation assessment, rehabilitation design, and post-rehabilitation validation. Finally, the chapter concludes with a comparative analysis of international standards, highlighting lessons and adaptations for Algeria's unique needs.

This chapter lays the foundation for practical implementation in subsequent chapters, where advanced techniques and materials will be evaluated for their suitability in addressing Algeria's seismic challenges. Through this effort, the proposed framework aims to significantly improve the seismic resilience of Algeria's RC infrastructure, aligning local practices with global advancements in structural engineering.

3.2 Overview of Algeria's Seismic Profile

Algeria's seismic vulnerability is driven by its geographic location on the Mediterranean seismic belt, a tectonically active region prone to frequent and destructive earthquakes. The combination of diverse soil conditions, varying seismic hazard zones, and historical

inadequacies in structural design has exposed the country’s RC infrastructure to significant risks. This section delves into Algeria’s seismic hazard zones, the historical performance of RC structures, and the influence of local soil and structural characteristics.

3.2.1 Algeria’s Seismic Hazard Zones

3.2.1.1 Overview of Algeria’s Tectonic Setting and Seismic Activity

Algeria is situated along the northern boundary of the African plate, adjacent to the highly active Mediterranean seismic belt. This tectonic setting is defined by the collision and subduction processes occurring between the African and Eurasian plates. The constant tectonic movement generates significant seismic activity, particularly along the northern coastal regions, which are densely populated and home to critical infrastructure.

The seismic hazards in Algeria arise from a combination of:

- A. Active Fault Systems:** Several significant faults, including the Cheliff and the Blida Fault, have been identified as contributors to seismic risk. Historical seismic events have evidenced that these faults can generate high-magnitude earthquakes.
- B. Shallow Earthquakes:** Most earthquakes in Algeria occur at shallow depths (less than 15 km), resulting in higher ground accelerations and amplified damage to structures.
- C. Geographic Distribution of Seismic Activity**
 - **Northern Algeria:** Experiences frequent moderate to high-magnitude earthquakes due to the proximity of active faults.
 - **Central and Southern Algeria:** Characterized by lower seismic activity due to the stability of the Saharan craton.

3.2.1.2 Classification of Seismic Zones as per RPA 99/2003

The RPA 99/2003 code defines five seismic zones based on the level of seismic hazard (see *Section 2.3.2.1 C, Geographical Seismic Hazard Zoning*, in *Chapter 2* for detailed zoning and regional considerations)

3.2.1.3 Historical Earthquakes and Their Impact on Infrastructure

Algeria has experienced numerous significant earthquakes, particularly in its northern region, which have often caused widespread destruction and highlighted the vulnerabilities of older structures not designed for seismic forces. Notable events include the El Asnam earthquake (1980, magnitude 7.3) and the Boumerdes-Algiers earthquake (2003, magnitude 6.8), among others, which resulted in substantial infrastructure damage and loss of life.

- **Notable Historical Earthquakes**

Table 3.1. Notable Historical Earthquakes in Algeria and Their Impact.

Event	Date	Magnitude	Region Affected	Impact

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Algiers Earthquake	02 Jan 1365	6.5–7.0	Algiers	Significant damage, loss of life.
Oran Earthquake	1790	7.0	Oran	Significant destruction of buildings.
Gouraya Earthquake	1891	6.7	Gouraya	Extensive damage to infrastructure.
Orleansville Earthquake	09 Sept 1954	6	Orleansville (Chlef)	Collapse of residential and commercial buildings.
El Asnam Earthquake	10 Oct 1980	7.3	El Asnam (Chlef)	Deadliest in Algeria's history; 2,500+ fatalities.
Constantine Earthquake	27 Oct 1985	6.0	Constantine	Moderate damage and increased awareness for seismic risks.
Tipaza Earthquake	29 Oct 1989	5.9	Tipaza	Moderate damage to older structures.
Mascara Earthquake	18 Aug 1994	5.8	Mascara	Damage to residential areas.
Ain Benian Earthquake	04 Sept 1996	5.7	Ain Benian (Algiers)	Significant damage to buildings, particularly older ones.
Ain Temouchent Earthquake	22 Dec 1999	5.6	Ain Temouchent	Moderate damage and structural vulnerabilities were highlighted.
Beni Ouartilane Earthquake	10 Nov 2000	5.2	Beni Ouartilane	Moderate damage, ongoing discourse on retrofitting.
Boumerdes-Algiers Earthquake	21 May 2003	6.8	Boumerdes, Algiers	Widespread destruction and reinforced seismic design are needed.

• Impact on Infrastructure and Building Codes

The lessons from these historical earthquakes have profoundly impacted the development of seismic building codes in Algeria. Following the catastrophic El Asnam earthquake in 1980, Algeria introduced stronger building regulations that culminated in the RPA 99/2003 seismic code designed to address the vulnerabilities exposed by these events. These events also highlighted the importance of retrofitting existing structures, as many buildings

affected by these earthquakes were poorly reinforced and lacked modern seismic design features.

3.2.2 Historical Performance of RC Structures in Algeria

3.2.2.1. Common Patterns of Failure in RC Structures During Past Earthquakes

Reinforced Concrete (RC) structures, despite being Algeria's most commonly used form of construction, tend to exhibit specific types of vulnerabilities during major seismic events. These vulnerabilities have been clearly illustrated by past earthquakes, including the Orleansville (1954), El Asnam (1980), and Boumerdes (2003) earthquakes. Common failure patterns observed in RC structures include:

A. Structural Instability and Collapse

One of the most notable failures in RC buildings has been collapse due to inadequate reinforcement and poor design. During the Boumerdes 2003 earthquake, large numbers of RC buildings collapsed or suffered severe damage, particularly in Algiers and Boumerdes provinces [37]. The causes of collapse were generally traced back to:

- **Weak foundation design:** In many cases, RC structures had insufficient foundations or improperly designed base slabs, leading to settlement or tilting during lateral shaking.
- **Insufficient reinforcement detailing:** Many buildings, especially older ones, had insufficient lateral reinforcement, which caused beams and shear walls to fail during horizontal seismic forces.
- **Poor-quality concrete:** Substandard concrete mixtures, especially before modern seismic codes, led to brittle behavior under seismic loading, with cracks and concrete spalling.



Fig 3.1. Collapse of Reinforced Concrete Structure in Boumerdes (2003) Earthquake Due to Weak Foundation Design.

B. Beam and Column Failures

Another typical pattern of failure has been observed in beam-column joints, which are typically the most vulnerable part of an RC structure during an earthquake. The lack of proper detailing of reinforcement in these connections often led to:

- **Failure at beam-column joints:** In buildings constructed before implementing modern seismic codes, these joints often lacked adequate reinforcement bars or proper anchorage, resulting in plastic hinge formation and column failure [38].



Fig 3.2. Column-Beam Failure Due to Insufficient Seismic Detailing in Zemmouri During the Boumerdes (2003) Earthquake [39].

- **Cracking and Spalling of Concrete:** During seismic shaking, the concrete beams and columns in older RC structures often cracked and experienced significant spalling, compromising structural integrity. In the Boumerdes (2003) earthquake, this type of damage was widespread in multi-story residential buildings [14].

C. Poor Floor Diaphragm Performance

The floor diaphragms of RC buildings often showed signs of failure during seismic events.

This failure can be attributed to:

- Lack of continuity and rigidity in the floor slab resulted in the displacement of upper floors relative to the building's foundation.
- Flexural weakness: The floors in older buildings were not designed with enough lateral resistance, causing floors to collapse when the structure underwent excessive lateral movement.



Fig 3.3. Damages to Roof Diaphragm at Re-Entrant Corner of West Anchorage High School During the 1964 Earthquake [40].

D. Differential Settling and Tilting

In some cases, differential settlement of the foundation led to the tilting of entire buildings. Poorly compacted soil, the use of inadequate foundation systems, and soil-structure interaction contributed to the tilting, especially in non-engineered structures built before modern codes.

Types of Settlement

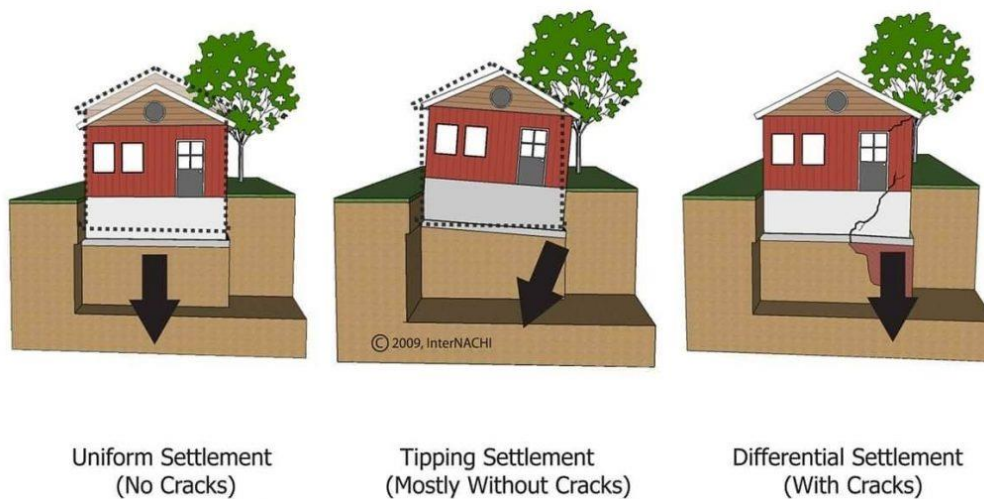


Fig 3.4. Types of Settlement: Illustration of Differential Settlement Leading to Building Tilting [41].

3.2.2.2. Insights from Post-Disaster Investigations

In-depth post-disaster investigations have provided valuable insights into the performance of RC structures during and after major earthquakes in Algeria. Some of the key findings from these investigations include:

A. El Asnam Earthquake (1980)

The El Asnam earthquake was one of the most devastating seismic events in Algeria's modern history. The earthquake's impact on RC structures highlighted several weaknesses in building practices:

- **Foundation Failures:** Investigations revealed that many RC buildings collapsed due to weak foundations, often caused by insufficient soil investigations and improper foundation design [15].
- **Inadequate Reinforcement:** Many buildings were found to have insufficient lateral reinforcement. The beam-column connections failed at a higher rate, indicating poor design and construction practices in older RC buildings.
- **Spalling of Concrete:** The earthquake caused widespread spalling of concrete in beams, columns, and walls, particularly in older buildings where concrete had degraded over time [42].



Fig 3.5. Foundation Failures and Structural Settlement in RC Buildings During the El Asnam (1980) Earthquake [15].

B. Boumerdes Earthquake (2003)

The Boumerdes earthquake led to a significant re-evaluation of RC building practices in Algeria. Post-earthquake studies revealed the following [14]:

- **Failure of Concrete Shear Walls:** In many multi-story RC buildings, shear walls were inadequately reinforced, leading to failure during lateral seismic motion. This issue was particularly evident in buildings built before the RPA 99/2003 seismic code.
- **Inadequate Seismic Detailing:** Investigations revealed that many older RC buildings had insufficient reinforcement detailing. In some cases, the

reinforcement bars were not properly anchored or were placed too far apart, leading to brittle failure.

- **Non-compliance with Seismic Codes:** The earthquake underscored the gap between design specifications and construction practices. Many buildings had been built without adherence to modern seismic codes, leading to significant structural damage.



Fig 3.6. Shearing of Corner Column Due to Lack of Transverse Confinement and Poor Seismic Detailing: Example of Non-Compliance with Seismic Codes.

3.3 Framework Design Methodology

Developing a tailored seismic assessment and rehabilitation framework for reinforced concrete (RC) structures in Algeria requires a systematic methodology that integrates local seismic conditions, structural behavior, and modern assessment techniques. This framework serves the dual purpose of enhancing seismic resilience and addressing the specific needs of Algeria's construction industry. The following subsections present the detailed methodology for designing such a framework, which ensures that post-rehabilitation performance is optimized and sustainable.

3.3.1 Objectives of the Framework

The key objectives of the framework are critical to its practical applicability and relevance within Algeria's seismic context. They address the core aim of improving structural resilience to earthquakes and adapting assessment and rehabilitation strategies to local conditions.

A. Enhancing Seismic Resilience and Post-Rehabilitation Performance

- The framework's ultimate goal is to enhance the seismic resilience of RC structures, ensuring they remain functional during and after an earthquake. This involves

identifying weaknesses in the original design and implementing rehabilitation measures that increase structural capacity, enhance ductility, and improve energy dissipation.

- Post-rehabilitation performance refers to ensuring that a building, after undergoing strengthening or repair, can perform at least at the life safety level (i.e., preventing collapse and allowing evacuation). The rehabilitation process is expected to bring the building closer to modern seismic standards, ensuring it is more resistant to future seismic events.
- The rehabilitation process also aims to improve buildings' sustainability, ensuring they meet long-term environmental, economic, and social criteria.

B. Tailoring Assessment and Rehabilitation Practices to Algeria's Conditions

- Seismic hazard variability across Algeria is a key factor that necessitates region-specific analysis. The framework integrates PGA, soil conditions, and regional seismic behavior to ensure accurate performance predictions.
- Algeria's resource limitations, such as material availability, skilled labor, and financial constraints, necessitate a cost-effective and resource-efficient rehabilitation strategy. Additionally, it must consider local construction practices (e.g., cementitious materials, steel reinforcements, and traditional foundation systems) that may differ from international norms.
- The assessment process accounts for regional variations in construction quality and building maintenance practices, ensuring the framework's adaptability to different cities and regions.

3.3.2 Workflow of the Assessment Framework

The Algeria-Specific Seismic Assessment Framework's workflow outlines the sequential steps required to assess, rehabilitate, and validate a reinforced concrete (RC) structure's seismic performance. The workflow integrates the components previously described, detailing how these components progress logically and interconnect to form a complete rehabilitation process. This ensures that the rehabilitation decision-making process is thorough, systematic, and based on reliable data and analysis.

The following workflow is divided into five key steps:

- 1. Data Collection**
- 2. Seismic Performance Evaluation**
- 3. Rehabilitation Strategy Design**

4. Post-Rehabilitation Validation

5. Decision-Making and Final Evaluation

With the workflow of the Algeria-Specific Seismic Assessment Framework outlined, we now focus on the specific components that form the foundation of each step in the framework. While the workflow provides an overarching view of the sequential steps required for assessing and rehabilitating a structure, the framework components detail the specific actions, methods, and tools used at each stage to achieve the desired seismic performance.

In the following section, we will explore the individual components that comprise the framework, outlining the tasks involved in the data collection, seismic performance evaluation, rehabilitation strategy design, post-rehabilitation validation, and decision-making process. These components provide the practical foundation for each step and ensure that the rehabilitation process is thorough and effective.

3.4 Framework Components

The Framework Components section comprehensively summarizes the essential elements and actions required at each seismic assessment and rehabilitation stage. In this section, we will explore in greater detail the specific tasks, tools, and techniques used to evaluate a building's seismic vulnerability, design effective rehabilitation strategies, and validate the success of those measures after rehabilitation.

The following sections will guide you through the step-by-step process of this framework, covering the pre-rehabilitation assessment, rehabilitation design, post-rehabilitation validation, and final decision-making. Each phase is critical in ensuring the building is thoroughly assessed and rehabilitated, enhancing its seismic resilience and safety.

Step 01: Data Collection

The evaluation of seismic performance requires the systematic collection of both structural data and site-specific data. These parameters provide the essential input for subsequent modeling, analysis, and rehabilitation design.

1.1. Structural Data Collection

- **Geometry and Structural System**

The building's height, number of stories, floor areas, and layout must be accurately recorded, supported by detailed drawings (plans and elevations). The structural system (moment-resisting frames, shear walls, braced frames, etc.) must be identified, as it governs the distribution of seismic forces. The building's function (residential, commercial, critical

facility) is also noted, since it defines performance objectives such as Immediate Occupancy for essential infrastructure.



Fig 3.7. Residential building in Tebessa-Algeria.

- **Material Properties**

∞ **Concrete:** Compressive strength (via standard tests), modulus of elasticity, Poisson's ratio, and density. According to RPA 99/2003, a minimum strength of 25 MPa is required for standard residential buildings.



Fig 3.8. Core drilling in reinforced concrete for material sampling and inspection.

∞ **Steel reinforcement:** Yield strength, grade (e.g., B400, B500 per NA 8634), diameter, spacing, and arrangement. These properties influence ductility and energy dissipation.

- **Uniformity:** General quality and homogeneity of materials should be verified to detect possible segregation or poor workmanship.

- **Reinforcement and Structural Detailing**

Key parameters include bar diameters, spacing, anchorage and lap lengths, and stirrup distribution. Columns and beams must be documented in terms of size, reinforcement, and expected seismic performance. Particular attention should be paid to beam–column connections in moment-resisting frames, as they are critical for ductility.

- **Condition Assessment**

The current state of the structure must be established through:

- ∞ Visual inspections for cracks, spalling, or deflection.
- ∞ Corrosion assessment of reinforcement (e.g., half-cell potential measurements).
- ∞ Non-destructive tests (NDT) such as rebound hammer or ultrasonic pulse velocity for concrete quality.
- ∞ Crack mapping to identify settlement or overloading issues.

1.2.Site-Specific Data

- **Soil Properties**

Soil classification, shear wave velocity (V_s), and foundation type are determined from geotechnical investigations. These parameters, as defined in RPA 99/2003, directly affect site classification and ground motion amplification.

- **Seismic Hazard Parameters**

- ∞ **Peak Ground Acceleration (PGA):** obtained from seismic hazard maps.
- ∞ **Seismic Zone:** Algeria’s zoning (0, I, IIa, IIb, III) establishes expected ground motion levels.
- ∞ **Design Spectra:** provided by RPA 99/2003, adapted to seismic zone, soil type, and building importance, and used in dynamic analysis.

- **Seismicity Data**

Regional seismicity records, including historical earthquake data and ground motion recordings, complement the hazard definition and enable realistic input for structural analysis.

Step 02: Seismic Performance Evaluation (Before Rehabilitation)

Following the collection of site-specific and structural data in Step 1, the second stage involves evaluating the seismic performance of the building in its existing state. This assessment establishes a baseline understanding of how the structure behaves under seismic loading and identifies its deficiencies prior to rehabilitation. The methodology integrates both local requirements (RPA 99/2003) and international frameworks (Eurocode 8, ASCE 41, FEMA 356), ensuring that the evaluation is comprehensive, performance-oriented, and adaptable to the Algerian context.

2.1.Seismic Performance Levels (SPLs)

Chapter 3: Algeria-Specific Seismic Assessment Framework

Performance-based seismic design requires defining target Seismic Performance Levels (SPLs), which represent the expected structural behavior under different levels of earthquake intensity. These performance levels, adapted for Algeria from international standards, include:

- **Immediate Occupancy (IO):**

The building remains fully functional after the earthquake, with no significant structural damage and only minor cosmetic damage to non-structural elements. This level is particularly required for essential facilities such as hospitals and emergency services.

- **Life Safety (LS):**

Structural and non-structural elements may sustain moderate damage, but collapse is prevented, and the safety of occupants is ensured. The building may not remain operational, but evacuation can be carried out safely.

- **Collapse Prevention (CP):**

Severe damage to structural elements is permitted, but total collapse must be avoided. The structure may be uninhabitable after the event, but catastrophic failure is prevented, preserving life safety.

- **Functional Recovery (FR): (Critical Infrastructure Only)**

Essential services (hospitals, communication centers) must resume operations quickly with minimal downtime. Both structural and non-structural components must sustain only limited damage to allow for rapid restoration of functionality.

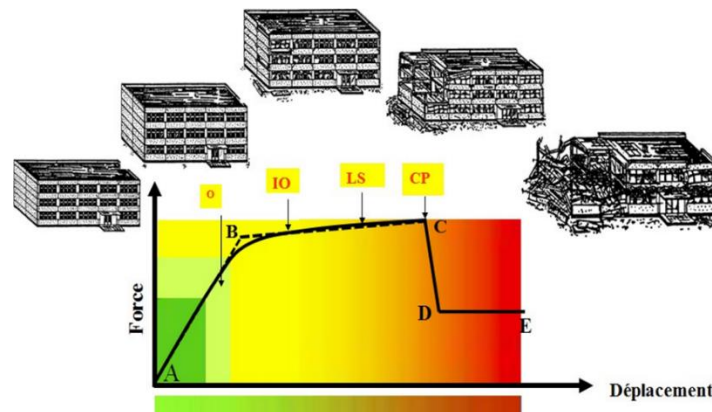


Fig 3.9. Force–Displacement Capacity Curve with Performance Levels (IO, LS, CP).

2.2. Structural Analysis Methods (Pre-Rehabilitation)

Different analysis methods are applied depending on the complexity of the structure, its seismic hazard level, and the required accuracy of the performance evaluation.

- **Linear Static Analysis (Equivalent Lateral Force Method):**

- ∞ A simplified elastic approach used mainly for regular, low-rise buildings.

- ∞ Lateral forces are distributed proportionally to mass and height, and structural members are checked against elastic limits.
- ∞ Useful for preliminary evaluation but limited in capturing nonlinear behavior, irregularity, or dynamic effects.
- **Nonlinear Static Analysis (Pushover Analysis):**
 - ∞ Incremental lateral forces are applied until the structure reaches its ultimate capacity.
 - ∞ Generates a capacity curve (force-displacement), identifying plastic hinge formation and potential collapse mechanisms.
 - ∞ Crucial for performance-based assessment, as it reveals inelastic behavior and failure modes.
- **Nonlinear Dynamic Analysis (Time-History Analysis):**
 - ∞ Uses real or synthetic earthquake records to simulate building response over time.
 - ∞ Incorporates material nonlinearities (cracking, yielding) and dynamic effects (resonance, damping).
 - ∞ Provides highly detailed results but requires significant computational effort and reliable ground motion data.
- **Modal and Response Spectrum Analysis:**
 - ∞ Identifies natural frequencies and vibration modes of the building.
 - ∞ Combines modal responses under a seismic design spectrum defined by RPA 99/2003.
 - ∞ Effective for capturing dynamic effects in complex or tall structures but remains an approximate linear method.

2.3. Vulnerability Assessment

Once the performance is evaluated, structural vulnerabilities must be identified. Common deficiencies in Algerian RC buildings include:

- ∞ **Weak or Short Columns:** Columns with insufficient reinforcement or poor detailing, prone to brittle failure.
- ∞ **Inadequate Ductility:** Lack of proper confinement and seismic detailing, leading to fragile collapse modes.
- ∞ **Soft Story Effect:** Discontinuities in stiffness (e.g., open ground floors) increasing collapse risk.
- ∞ **Non-Continuous Load Paths:** Weak diaphragms or poor connections interrupting seismic force transfer.

- ∞ **Foundation Instability:** Poor soil conditions or weak foundations contributing to settlement or tilting.
- ∞ **Outdated Construction Practices:** Older buildings often lack compliance with modern seismic codes, relying on lower material grades and insufficient detailing.



Fig 3.10. Vulnerability of short columns under seismic loading.

2.4. Seismic Capacity vs. Demand Comparison

The final step in pre-rehabilitation evaluation compares the structural capacity with the seismic demand expected at the site:

- **Strength Assessment:** Elemental capacities (beams, columns, shear walls) are compared against seismic demands from hazard parameters.
- **Ductility and Energy Dissipation:** The ability of the structure to deform plastically without collapse is checked against performance targets (LS, CP).
- **Safety Margins:** Deficiencies are quantified, identifying components that fall short of required performance and require strengthening.

This comparison defines the gap between current performance and target SPLs, providing the basis for selecting appropriate rehabilitation strategies.

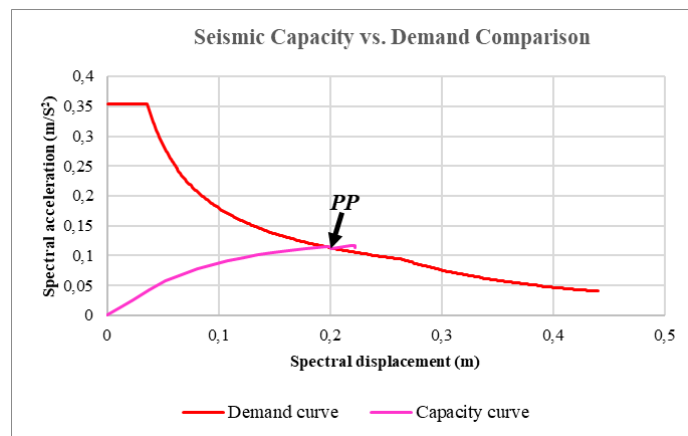


Fig 3.11. Performance Point Determination using the Capacity Spectrum Method.

Step 03: Rehabilitation Strategy Design

The aim of rehabilitation strategy design is to restore or enhance the seismic resilience of structures previously identified as vulnerable in *Step 02: Seismic Performance Evaluation*. The choice of rehabilitation measures depends on the severity of observed damage and the existing condition of the building. This process involves three key stages: (i) classification of structural damage, (ii) selection of appropriate materials, and (iii) application of rehabilitation techniques, followed by verification through advanced analytical methods.

3.1. Damage Classification

Damage classification provides a systematic basis for determining the level of intervention required. Based on seismic performance evaluation (pushover or nonlinear dynamic analysis), three levels of damage are identified:

- **Minor Damage:** Limited to non-structural elements with negligible impact on global stability. Examples include hairline cracks in plaster or minor partition deformations. Rehabilitation focuses on non-structural repairs, cosmetic restoration, and monitoring through inspections and non-destructive testing.
- **Moderate Damage:** Characterized by cracking or localized degradation of structural components (beams, columns, slabs), while overall stability is maintained. Rehabilitation measures include concrete or steel jacketing, FRP strengthening, foundation repairs, and targeted non-structural replacement. This level typically requires a comprehensive plan to restore seismic performance to life-safety levels.
- **Severe Damage:** Involves critical damage to load-bearing elements (e.g., column failure, shear wall spalling, or foundation settlement), threatening overall stability. The structure may become uninhabitable and require extensive interventions such as replacement of collapsed elements, advanced retrofitting with UHPC, FRP, or SMA, installation of base isolation systems, or addition of steel bracing and energy dissipation devices.



Fig 3.12. Façade Detachment and Partial Collapse of Upper, Intermediate, or Lower Stories.



Fig 3.13. Failure of Vertical Load-Bearing Elements under Seismic Loading [43].

3.2. Material Selection

Material choice is crucial to ensuring effective and durable rehabilitation. Advanced materials are increasingly adopted in seismic retrofitting:

- Fiber Reinforced Polymers (FRP): Lightweight, corrosion-resistant, and highly effective in strengthening beams, slabs, and columns. CFRP is commonly used for tension-dominated elements, while GFRP provides cost-effective alternatives in corrosive environments.
- Shape Memory Alloys (SMA): Innovative materials capable of self-centering and energy dissipation, improving ductility and post-earthquake recovery.
- Ultra-High-Performance Concrete (UHPC): Applied to columns and shear walls, UHPC significantly improves load-bearing capacity and seismic resistance.
- Locally Available Materials: The use of locally produced steel reinforcement and traditional concrete, in combination with modern strengthening methods, reduces costs and ensures feasibility in Algerian practice.

3.3. Rehabilitation Techniques

Several techniques are available to enhance seismic resilience:

- Jacketing (Steel, Concrete, or FRP): Increases the strength and ductility of columns, beams, and shear walls.
- Base Isolation: Reduces seismic demand on the superstructure by decoupling it from ground motion, especially valuable for essential facilities.
- Energy Dissipation Devices: Includes viscous, friction, or tuned mass dampers to absorb seismic energy and control displacements.
- Steel Bracing Systems: Both concentric and eccentric configurations improve lateral resistance and energy dissipation.

- Buckling-Restrained Braces (BRB): Provide high ductility and prevent strength loss under compression.
- Foundation Strengthening: Through underpinning, piles, or widening of footings to address settlement and enhance stability.

3.4. Advanced Analytical Methods

Post-rehabilitation performance must be verified through advanced numerical simulations:

- Pushover Analysis evaluates nonlinear capacity, ensuring plastic hinges form in non-critical regions and that ductility is enhanced.
- Dynamic Simulations (time-history and response spectrum analyses) validate the rehabilitated building's response under realistic seismic scenarios, verifying reductions in story drifts, accelerations, and residual deformations.
- Performance-Based Design (PBD) ensures the structure meets predefined performance objectives (Immediate Occupancy, Life Safety, or Collapse Prevention) under design and maximum-considered earthquakes.

These methods collectively verify that the adopted rehabilitation measures effectively improve strength, stiffness, and ductility, ensuring resilience against future seismic events.

Step 04: Post-Rehabilitation Validation

Post-rehabilitation validation is essential to ensure that the applied rehabilitation measures perform as intended under real-world seismic conditions. This phase moves beyond theoretical analysis by incorporating field testing, monitoring, and feedback to confirm that the rehabilitated structure meets the targeted seismic performance objectives. It also allows refinement of strategies based on practical observations and real data.

4.1. Performance Benchmarks

Before validating the performance of the rehabilitated structure, it is essential to define the performance benchmarks that the building must meet. These benchmarks are based on the performance-based design criteria established earlier in the process and correspond to specific seismic performance levels. The performance benchmarks might include:

- ∞ Immediate Occupancy (IO): The building must remain safe and functional immediately after an earthquake without requiring major repairs or significant downtime.
- ∞ Life Safety (LS): The structure must protect the occupants from collapse, ensuring safe evacuation while suffering moderate to significant damage that is repairable.
- ∞ Collapse Prevention (CP): The building must prevent total failure during extreme seismic events, even if substantial damage occurs. This is typically the goal for buildings in high seismic zones.

- ∞ **Functional Recovery (FR):** For critical infrastructure, the building should be able to resume operation quickly with minimal repairs or disruptions.

These benchmarks form the foundation for the post-rehabilitation validation process, where the performance of the rehabilitated building is tested and compared against these targets.

4.2. Validation Techniques

Several techniques, including nondestructive testing (NDT), structural health monitoring (SHM), and real-world case studies, can be used to validate the structure's post-rehabilitation performance. These techniques help ensure that the structure's performance matches the predictions made during the analytical assessments.

- **Non-Destructive Testing (NDT)**

NDT methods are used to assess the structural integrity of the rehabilitated building without causing damage. These techniques help detect issues such as cracking, delamination, or corrosion in structural elements.

- ∞ **Ultrasonic Pulse Velocity Testing:** This method detects cracks and voids in concrete, which may indicate structural weaknesses that could affect the building's seismic performance.
- ∞ **Ground-Penetrating Radar (GPR):** Used to detect reinforcement placement and concrete integrity, GPR can identify areas where the reinforcement might have been damaged or where moisture accumulation could affect the structure.
- ∞ **Rebound Hammer Test:** This is a rapid method for assessing the surface hardness of concrete, which correlates to the material's compressive strength. A rebound hammer test can help identify areas where the concrete has weakened after the earthquake and subsequent rehabilitation.



Fig 3.14. Non-Destructive Testing Methods for Concrete Evaluation [44].

- **Field and Case Studies**

Field and case studies of similar rehabilitated buildings are useful for comparing actual performance with theoretical predictions. Observations from post-earthquake events or from rehabilitated buildings in other locations can provide real-world data on the effectiveness of specific rehabilitation techniques.

- **Post-Earthquake Inspections:** After a major seismic event, post-earthquake inspections of rehabilitated buildings provide real-time feedback on how the building performs under actual seismic loading. Engineers can assess whether the rehabilitation measures successfully achieved the desired performance levels.
- **Comparison with Similar Buildings:** Case studies of buildings that underwent similar rehabilitation measures can provide valuable insights into the likely performance of the rehabilitated structure. These studies often highlight common issues and suggest refinements to the rehabilitation process.
- **Feedback Mechanisms**

Feedback from stakeholders is an essential part of the post-rehabilitation validation process. This feedback can come from engineers, policymakers, building owners, and occupants and provides valuable insights into the real-world performance of the rehabilitated building.

- ∞ **Engineers:** Feedback from engineers who conduct post-event inspections can reveal discrepancies between predicted and observed performance, leading to refinements in future rehabilitation strategies.
- ∞ **Policymakers:** Insights from local building authorities or policymakers can help ensure that rehabilitation strategies align with regional seismic safety goals.
- ∞ **Building Occupants:** Feedback from the building's occupants about post-event functionality (e.g., evacuation times, operational capacity) provides essential information on whether the rehabilitation measures have effectively restored or enhanced the building's functionality after a seismic event.

Incorporating Feedback into Future Designs

One of the critical aspects of post-rehabilitation validation is learning from feedback to improve future designs. This includes:

- ∞ Adjusting rehabilitation techniques to address any issues identified during validation (e.g., adding additional bracing or improving energy dissipation).
- ∞ Revising building codes or rehabilitation guidelines based on real-world performance data to enhance seismic resilience in future projects.

4.3.Key Parameters for Post-Rehabilitation Validation

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Several critical performance parameters need to be verified during post-rehabilitation validation to ensure that the rehabilitation efforts have been successful:

- ∞ **Plastic Deformations:** Verify that the rehabilitated building can withstand seismic forces without excessive plastic deformations that would compromise its structural integrity.
- ∞ **Story Drifts:** Ensure that story drifts remain within acceptable limits, as excessive drift can cause damage to both structural and non-structural components.
- ∞ **Residual Displacements:** Verify that the building experiences minimal residual deformations after a seismic event. This indicates that the rehabilitation measures (such as energy dissipation devices or base isolation) have successfully minimized permanent damage.
- ∞ **Energy Dissipation:** Confirm that energy dissipation devices function as expected, effectively reducing seismic forces transmitted to the structure and limiting damage to critical elements.
- ∞ **Seismic Performance Levels:** Finally, compare the building's actual performance with the desired performance objectives (e.g., life safety, collapse prevention, immediate occupancy) to ensure that the rehabilitation measures have achieved the intended results.

Post-rehabilitation validation is a crucial step to ensure that the rehabilitation techniques have achieved the desired seismic performance objectives. Engineers can verify that the rehabilitated building performs as intended under real-world seismic conditions by using non-destructive testing (NDT), field studies, and case studies. The validation process helps ensure that the building will provide life safety, collapse prevention, or immediate occupancy as required and that the rehabilitation measures have effectively enhanced seismic resilience. Through feedback mechanisms, engineers can refine future rehabilitation efforts to improve the safety and performance of buildings in seismic regions.

With the validation process completed and the rehabilitated building shown to meet the desired performance objectives, the next critical step is to make an informed decision about the structure's overall seismic safety and resilience classification. This decision is based on the performance indicators gathered from the validation phase and the results from post-rehabilitation testing.

Step 05: Decision-Making and Final Evaluation

Step 5: Decision-Making and Final Evaluation marks the final stage of the rehabilitation framework, where the structure's seismic performance is assessed, and a final decision is made

regarding its seismic resilience and functional safety. Based on the results of the previous steps, particularly the post-rehabilitation validation, a comprehensive performance classification is assigned to the building. This classification reflects its ability to withstand seismic events and meet the required performance objectives.

5.1. Seismic Performance Classification

Based on the results from pushover analysis, dynamic simulations, non-destructive testing (NDT), structural health monitoring (SHM), and feedback from field studies, the building is assigned a final seismic performance classification. This classification is based on how well the rehabilitated structure meets the performance criteria established in earlier stages. The performance classification reflects the building's seismic resilience and defines its post-rehabilitation status.

The performance levels are as follows:

A. Immediate Occupancy (IO):

The building can be safely occupied immediately after an earthquake, with only minor non-structural damage. The structure is fully functional and requires minimal repairs to resume normal operations.

- ∞ **Performance Indicators:** No significant structural damage; minor cracks in finishes and non-load-bearing walls; minimal displacement or deformation of structural elements.
- ∞ **Action:** The building is cleared for immediate use, providing minimal disruption to occupants or operations.

B. Life Safety (LS):

The building is safe for occupancy, ensuring that occupants can evacuate safely. While the structure may experience moderate damage (especially to non-structural elements), it remains stable and capable of withstanding aftershocks without collapse.

- ∞ **Performance Indicators:** Moderate structural damage (e.g., cracks in beams, columns, and shear walls), but no risk of collapse; damage to non-structural components (e.g., partitions, windows).
- ∞ **Action:** The building may require repairs but remains operational for emergency functions or temporary occupancy.

C. Collapse Prevention (CP):

The building is designed to prevent catastrophic collapse during a major seismic event, though it may suffer significant damage that requires extensive repairs.

- ∞ **Performance Indicators:** Major structural damage, but the building maintains stability; failure of non-structural components; serious deformation or cracks in key structural elements, but no risk of total collapse.
- ∞ **Action:** The building will need extensive repairs before it can be safely occupied again. The structure prevents collapse, but further reinforcement may be necessary.

5.2.Key Performance Indicators

In determining the final seismic performance classification, several key performance indicators were considered during the post-rehabilitation validation process:

- ∞ **Plastic Hinges:** After rehabilitation, the structure must show that plastic hinges form in controlled locations (such as beams or shear walls) and not in critical elements (e.g., columns) that would lead to collapse.
- ∞ **Story Drifts:** The rehabilitated building must ensure that inter-story drifts (lateral displacements between floors) are within acceptable limits defined by performance objectives. Excessive drifts can cause structural damage or make the building unsafe for occupancy.
- ∞ **Residual Deformations:** After a seismic event, residual displacements (permanent deformations in structural components) should be minimal, indicating that the structure has returned to its pre-event condition or within a tolerable range.
- ∞ **Energy Dissipation:** Energy dissipation devices (e.g., dampers, base isolators) should function as intended, reducing the seismic forces transmitted to the building and ensuring that the structure does not experience excessive vibrations, swelling, or displacements during the event.

5.3.Final Evaluation and Decision-Making

The final decision regarding the building's seismic performance is based on a synthesis of all the data collected during the rehabilitation process, including the results from pushover analysis, dynamic simulations, and real-world feedback.

The final seismic performance classification determines the building's suitability for use in the event of a seismic event, and whether it will be suitable for immediate re-occupancy, if repairs are needed, or if additional retrofitting is required to meet seismic safety standards.

- **Decision-Making Process:**

- ∞ **Review of Post-Rehabilitation Testing:** Assess whether the building meets the required performance levels (Immediate Occupancy, Life Safety, or Collapse Prevention).

- ∞ **Final Performance Classification:** Assign the building to one of the three performance categories based on the testing results and performance indicators.
- ∞ **Confirming Compliance with Seismic Standards:** Ensure the rehabilitated building meets the latest seismic codes, including local regulations or international standards (e.g., RPA 99/2003, Eurocode 8, ASCE/SEI 41).
- ∞ **Actionable Next Steps:** If the structure is classified under life safety or collapse prevention, specific repairs or further strengthening measures to enhance seismic resilience should be recommended.

5.4. Recommendations for Ongoing Monitoring or Maintenance

Based on the final seismic performance classification, the following recommendations are made for ongoing monitoring and maintenance:

- **For Immediate Occupancy (IO):**
 - ∞ Routine inspections should be conducted periodically to ensure that the seismic rehabilitation measures continue to perform as expected over time.
 - ∞ Structural health monitoring (SHM) should be implemented for long-term performance tracking, especially in critical infrastructure.
- **For Life Safety (LS):**
 - ∞ Periodic inspections should identify and address minor cracks or deficiencies that could worsen over time.
 - ∞ Post-event inspections should be scheduled after any significant seismic events to ensure the building remains safe for occupancy.
- **For Collapse Prevention (CP):**
 - ∞ Comprehensive inspections and repair works should be undertaken as soon as possible. The structure should be reinforced where necessary, especially in areas identified as vulnerable during the post-rehabilitation validation phase.
 - ∞ Extensive retrofitting might be necessary to bring the building to a Life Safety or Immediate Occupancy level of performance.

5.5. Regulatory Compliance and Future Use

Finally, based on the final classification and the results from “*Step 4: Post-Rehabilitation Validation*”, the building’s future use and occupancy status will be determined:

- ∞ **For Immediate Occupancy:** The building is cleared for re-occupation and should be able to resume normal operations with minimal repairs, ensuring functional recovery after a seismic event.

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- ∞ For Life Safety: The building may be used for temporary occupancy, but extensive repairs will be required to ensure that it can be safely re-occupied and used for normal functions.
- ∞ For Collapse Prevention: The building will need extensive repairs and reinforcement to prevent catastrophic collapse in future seismic events. It is not fit for occupancy until these repairs are made.

The building's compliance with seismic regulations (e.g., local building codes and international seismic standards) will also be verified and updated to ensure it meets current requirements.

Step 5: Decision-making and Final Evaluation serve as the final check of the building's seismic performance after rehabilitation, assigning it a performance classification based on the results from the validation process. By reviewing the building's performance indicators, the final decision ensures that the structure meets the seismic safety requirements necessary for occupancy or future use. Recommendations for further monitoring, maintenance, or repairs ensure that the building continues to meet seismic safety standards and remains resilient against future seismic events.

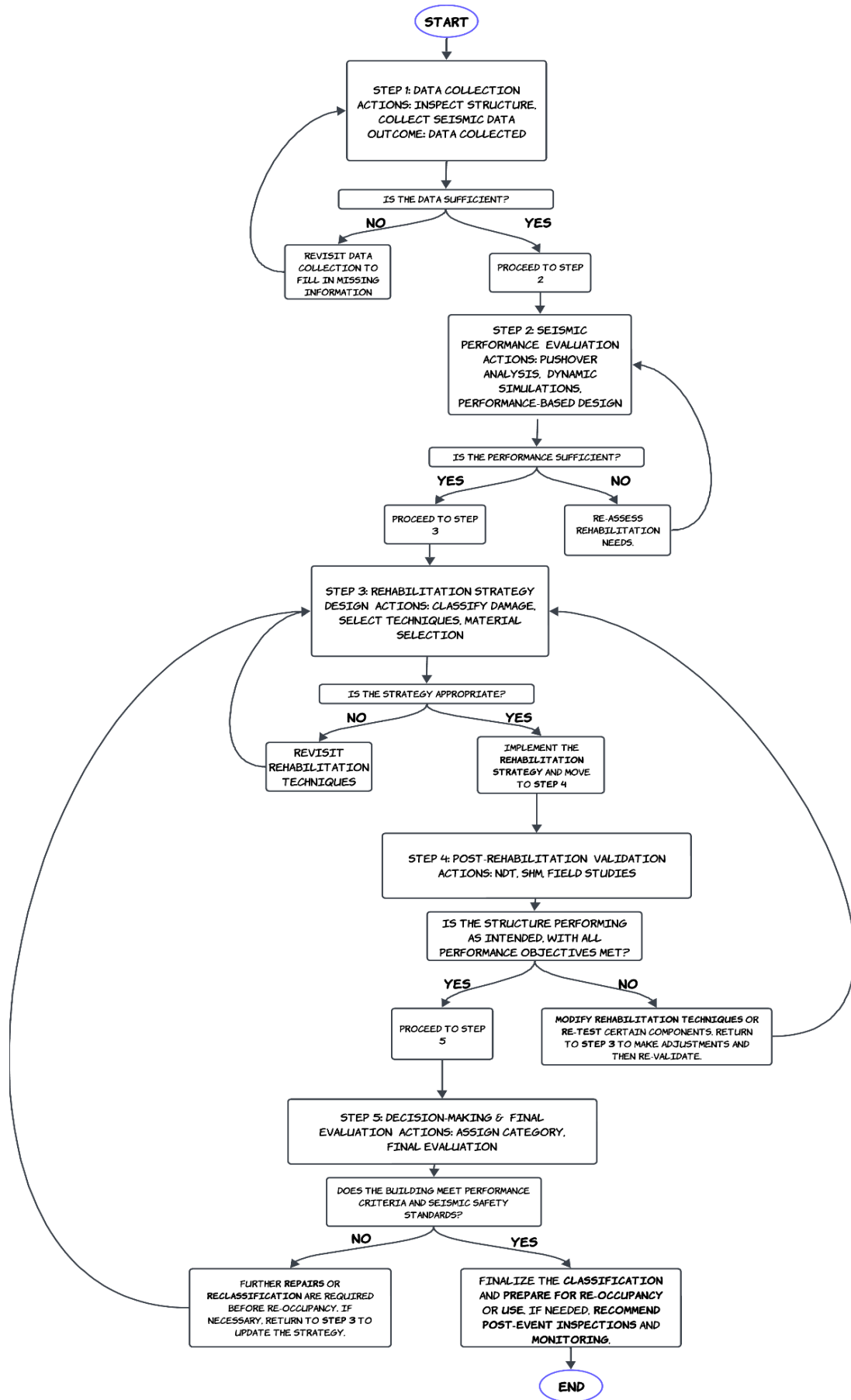


Fig 3.15. Framework for Seismic Performance Evaluation and Rehabilitation Strategy.

3.5 Comparative Analysis with International Standards

In this section, we perform a comparative analysis of the Algeria-Specific Seismic Assessment Framework, which was developed to address the shortcomings of RPA 99/2003—particularly its lack of a comprehensive methodology to assess the seismic performance and rehabilitation capacity of reinforced concrete (RC) structures after rehabilitation. The framework developed in this thesis introduces a systematic, performance-based approach to assessing and rehabilitating RC structures that fills the gaps left by the current RPA 99/2003 guidelines.

The international seismic frameworks selected for comparison include:

- ASCE/SEI 41: Seismic Rehabilitation of Existing Buildings (USA)
- Eurocode 8: Design of Structures for Earthquake Resistance (Europe)
- ACI 318: Building Code Requirements for Structural Concrete (USA)

This analysis aims to benchmark the Algeria-Specific Seismic Assessment Framework against these internationally recognized standards and identify the similarities, differences, and opportunities for improvement. This will provide insight into how the framework can be integrated into the existing Algerian seismic codes (like RPA 99/2003) to enhance its rehabilitation capabilities for RC structures.

3.5.1. Seismic Hazard Assessment

Table 3.2. Comparison of Seismic Hazard Assessment Methodologies: Algeria-Specific Framework vs. International Codes.

Criteria	Algeria-Specific Seismic Assessment Framework	ASCE/SEI 41	Eurocode 8	ACI 318
Seismic Hazard Data	Site-specific seismic data, including PGA, soil amplification factors, and local ground motions	Uses site-specific seismic data, considers soil amplification	Comprehensive seismic hazard, including PGA, soil conditions, and amplification factors	Broad seismic zones, but no detailed site-specific data
Seismic Zone Classification	Based on PGA, incorporating local variations in seismic risk	Uses site-specific seismic data and considers local soil effects	Integrates PGA and soil interaction for more accurate hazard analysis	Uses PGA for seismic hazard but lacks detailed site-specific parameters
Consideration of Soil-Structure Interaction	Included, considering local soil conditions	Included with emphasis on soil conditions	Included, with detailed soil-structure interaction models	Not included; more generalized for typical conditions

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- ∞ **Key Takeaway:** The developed framework provides a more comprehensive seismic hazard assessment by incorporating site-specific seismic data and soil-structure interaction, making it more accurate compared to *ACI 318*, which uses generalized seismic zone classifications.

3.5.2. Damage Classification and Performance-Based Design

Table 3.3. Comparison of Damage Classification Systems and Performance-Based Design: Algeria-Specific Framework vs. International Codes

Criteria	Algeria-Specific Seismic Assessment Framework	ASCE/SEI 41	Eurocode 8	ACI 318
Damage Classification	Minor, Moderate, Severe linked to performance objectives (IO, LS, CP)	Performance-based damage states with clear damage levels linked to performance objectives	Classifies damage linked to performance levels such as life safety and reparability	Basic visual inspection, lacks a robust performance-based classification
Performance Objectives	Linked to Immediate Occupancy, Life Safety, and Collapse Prevention	Defined in terms of performance objectives such as Immediate Occupancy, Life Safety, and Collapse Prevention	Defines performance levels for different seismic events and repairs	Does not integrate performance-based objectives in rehabilitation
Post-Rehabilitation Evaluation	Quantitative evaluation of rehabilitation effectiveness	Evaluates rehabilitation performance post-event	Similar to ASCE/SEI 41, focuses on performance after intervention	No clear methodology for post-rehabilitation evaluation

Key Takeaway: The developed framework stands out by integrating performance-based damage classification and linking rehabilitation strategies to desired performance outcomes, which is a significant improvement over ACI 318, which lacks a clear performance-based design for rehabilitation.

3.5.3. Rehabilitation Techniques and Materials

Table 3.4. Comparison of Rehabilitation Techniques and Advanced Materials: Algeria-Specific Framework vs. International Codes

Criteria	Algeria-Specific Seismic Assessment Framework	ASCE/SEI 41	Eurocode 8	ACI 318
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Rehabilitation Techniques	Includes base isolation, energy dissipation devices, jacketing, FRP strengthening, and SMA	Emphasizes base isolation, energy dissipation devices, and FRP	Comprehensive, including base isolation, energy dissipation devices, SMA, and FRP	Primarily focuses on jacketing and reinforcement
Use of Advanced Materials	FRP, Shape Memory Alloys (SMA), Ultra High-Performance Concrete (UHPC)	Advanced materials like FRP and SMA	Includes use of FRP, SMA, and UHPC for strengthening	Limited guidance on advanced materials
Innovation in Seismic Retrofit	Advanced techniques like base isolation, energy dissipation, and innovative materials	Incorporates innovative materials and technologies	Strong emphasis on innovative techniques for retrofitting	Basic retrofitting methods with little focus on innovative techniques

Key Takeaway: The developed framework is aligned with ASCE/SEI 41 and Eurocode 8 in its use of advanced rehabilitation techniques but goes a step further by incorporating innovative materials such as SMA and UHPC. ACI 318, however, does not include these advanced methods or materials.

3.5.4. Economic Feasibility and Sustainability

Table 3.5 Comparison of Economic Feasibility and Sustainability Considerations: Algeria-Specific Framework vs. International Codes

Criteria	Algeria-Specific Seismic Assessment Framework	ASCE/SEI 41	Eurocode 8	ACI 318
Economic Feasibility	Includes cost-benefit analysis and life-cycle cost evaluations	Incorporates life-cycle cost analysis and economic feasibility of rehabilitation	Similar to ASCE/SEI 41, it includes life-cycle costs and economic viability	No clear structure for cost-benefit analysis
Sustainability Considerations	Focus on sustainable materials and long-term performance	Encourages energy-efficient solutions and sustainable practices	Emphasizes sustainability in materials and rehabilitation techniques	Lacks significant emphasis on sustainability
Cost-Effective Solutions	Prioritizes cost-effective rehabilitation measures for Algeria's context	Focus on balancing seismic resilience with affordable solutions	Offers cost-effective strategies without compromising seismic safety	Primarily focuses on basic seismic safety without detailed cost analysis

Key Takeaway: The developed framework introduces a more structured approach to economic feasibility through cost-benefit analysis and life-cycle assessments, which is not emphasized in

ACI 318. It aligns closely with ASCE/SEI 41 and Eurocode 8 in promoting sustainable and cost-effective solutions for seismic rehabilitation.

3.5.5. Summary of Comparative Validation

The Algeria-Specific Seismic Assessment Framework has been validated compared with ASCE/SEI 41, Eurocode 8, and ACI 318, demonstrating its alignment with international best practices in several critical seismic assessment and rehabilitation areas. The developed framework not only addresses the gaps in RPA 99/2003 but also integrates advanced methodologies that enhance its relevance and effectiveness in the context of Algerian seismic risk.

- ∞ The framework aligns with performance-based design principles and advanced rehabilitation techniques that are commonly seen in ASCE/SEI 41 and Eurocode 8, setting it apart from the more traditional force-based approach used in ACI 318 and RPA 99/2003.
- ∞ By incorporating site-specific seismic data, advanced materials, and cost-benefit analysis, the framework presents a holistic, sustainable approach to rehabilitating RC structures, ensuring that rehabilitation efforts are both technically effective and economically feasible.

In conclusion, the framework has been validated as a comprehensive and innovative methodology for seismic rehabilitation in Algeria, positioning it alongside the most recognized and established international seismic standards.

3.6 Conclusion

In this chapter, we have developed the Algeria-Specific Seismic Assessment Framework, a comprehensive methodology designed to assess and rehabilitate RC structures in Algeria. This framework was carefully crafted to address the limitations of RPA 99/2003, which lacks a systematic approach for assessing seismic performance after rehabilitation. By integrating key principles from international seismic standards like ASCE/SEI 41, Eurocode 8, and ACI 318, the framework offers a performance-based approach to rehabilitation, emphasizing site-specific seismic data, advanced rehabilitation techniques, and economic feasibility.

The framework introduces several innovations, including:

- ∞ The use of site-specific seismic hazard data to account for local variations in soil conditions and seismic risk.
- ∞ The integration of performance-based design (PBD) principles to ensure that buildings meet specific seismic performance levels (e.g., life safety, collapse prevention).

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- ∞ The adoption of advanced rehabilitation techniques such as base isolation, energy dissipation devices, and innovative materials like FRP and SMA.

Through a comparative analysis with international standards, it was demonstrated that the Algeria-Specific Seismic Assessment Framework aligns with global best practices in seismic rehabilitation. It not only fills the critical gaps in RPA 99/2003 but also offers a more comprehensive, contextually relevant, and flexible solution to improve the seismic resilience of RC structures in Algeria.

To further build upon this framework, Chapter 4 delves into advanced numerical modeling techniques to evaluate the seismic behavior of RC structures. Using ETABS software, critical parameters such as ductility, damping mechanisms, and nonlinear structural behavior are analyzed to assess and enhance seismic resilience. These advanced modeling tools allow for a deeper understanding of RC structures' dynamic responses, setting the stage for validating the Algeria-Specific Seismic Assessment Framework in practical scenarios. This will be explored in the subsequent chapters through case studies and real-world applications.

***Chapter 4: Numerical Modeling for
Seismic Performance Assessment of
Reinforced Concrete Structures***

*“In the
digital realm, concrete breathes again — reborn through nodes, elements,
and equations”*

4.1 Introduction

Assessing seismic performance and enhancing the resilience of reinforced concrete (RC) structures have become pivotal considerations in earthquake engineering. In regions with significant seismic activity, such as Algeria, ensuring the ability of existing infrastructure to withstand the forces generated by earthquakes is paramount. While design codes like the Algerian Seismic Code (RPA 99/2003) provide guidelines for the initial design of RC structures, evaluating their performance post-rehabilitation, particularly under seismic loading, remains challenging.

Numerical modeling has emerged as a critical tool in the seismic assessment and rehabilitation of RC structures. By simulating the behavior of structures under dynamic loads, engineers can predict how various materials and retrofitting techniques will perform during an earthquake. This chapter focuses on using ETABS software, a powerful tool for structural analysis, to model RC structures before and after rehabilitation. ETABS offers linear and nonlinear analysis capabilities, allowing for detailed evaluations of structural performance, including the effects of advanced rehabilitation techniques.

Rehabilitation methods, such as the use of fiber-reinforced polymers (FRPs), shape-memory alloys (SMAs), and energy dissipation devices, have proven to enhance the seismic resilience of RC structures significantly. These techniques aim not only to improve the structure's strength but also to increase its ability to dissipate seismic energy and resist deformation, thereby preventing catastrophic failure during an earthquake. This chapter will explore the implementation of these advanced rehabilitation strategies in the numerical models, demonstrating how they can improve the seismic resilience of RC structures, ensuring their performance meets predefined safety thresholds.

Furthermore, the chapter integrates the principles of performance-based design (PBD), which offers a modern approach to evaluating the effectiveness of rehabilitation. By focusing on the expected performance of the structure after rehabilitation, PBD establishes clear objectives for post-earthquake functionality, including categories such as immediate occupancy, life safety, and collapse prevention.

Through detailed numerical simulations and performance evaluations, this chapter aims to provide a comprehensive understanding of how modern rehabilitation techniques can improve the seismic resilience of RC structures in Algeria, a region prone to significant seismic events. The chapter will also assess the feasibility of implementing these techniques locally, considering material availability, costs, and environmental factors.

4.2 Numerical Modeling Using ETABS

4.2.1 Overview of ETABS Software for Seismic Analysis

ETABS (Extended Three-Dimensional Analysis of Building Systems) [45] is one of the most widely used structural engineering software tools for modeling and analyzing the behavior of buildings and other structures under various loading conditions. In the context of seismic analysis, ETABS offers a robust platform for the design, evaluation, and rehabilitation of reinforced concrete (RC) structures, providing both linear and nonlinear analysis capabilities. This software is particularly valuable for assessing the seismic performance of existing structures, simulating the effects of rehabilitation measures, and predicting the response to earthquake-induced forces.

4.2.1.1 Capabilities of ETABS for Modeling, Simulating, and Analyzing RC Structures

ETABS supports various structural analysis tasks, from simple linear analyses to more complex nonlinear behavior simulations. The software can model various structural elements, including beams, columns, slabs, walls, and foundations. For RC structures, ETABS offers extensive material and element libraries, enabling users to accurately model the nonlinear behavior of concrete, steel, and composite materials.

Key capabilities of ETABS relevant to seismic analysis include:

- ✚ **Comprehensive Structural Modeling:** ETABS can model 2D and 3D structures, including complex geometries, nonlinear behavior, and multi-story buildings. The software allows users to define custom material properties, including concrete, reinforcement, and other materials used in rehabilitation.
- ✚ **Dynamic and Static Load Analysis:** ETABS supports both static and dynamic loading conditions, making it an essential tool for seismic analysis. Users can apply earthquake forces as per building codes or seismic standards, including those based on response spectra or time-history analysis.
- ✚ **Linear and Nonlinear Analysis:** ETABS provides the flexibility to conduct both linear and nonlinear seismic analyses. Nonlinear static (pushover) and dynamic analyses allow for the simulation of more realistic earthquake responses, including structural yielding and post-elastic behavior.
- ✚ **Response Spectrum and Time-History Analysis:** ETABS supports advanced seismic analysis methods, including response spectrum analysis, widely used in seismic design, and time-history analysis, which simulates the structure's response to specific earthquake records.

- ✚ **Pushover Analysis:** This is a nonlinear static procedure used to evaluate a structure's capacity by incrementally applying lateral loads and assessing its displacement. It is particularly valuable for evaluating the effectiveness of rehabilitation techniques in enhancing the seismic performance of RC structures.
- ✚ **Seismic Performance Evaluation:** ETABS allows engineers to perform comprehensive performance evaluations of structures under earthquake loading, which includes the evaluation of displacement, drift, inter-story drift, base shear, and other key seismic performance indicators.

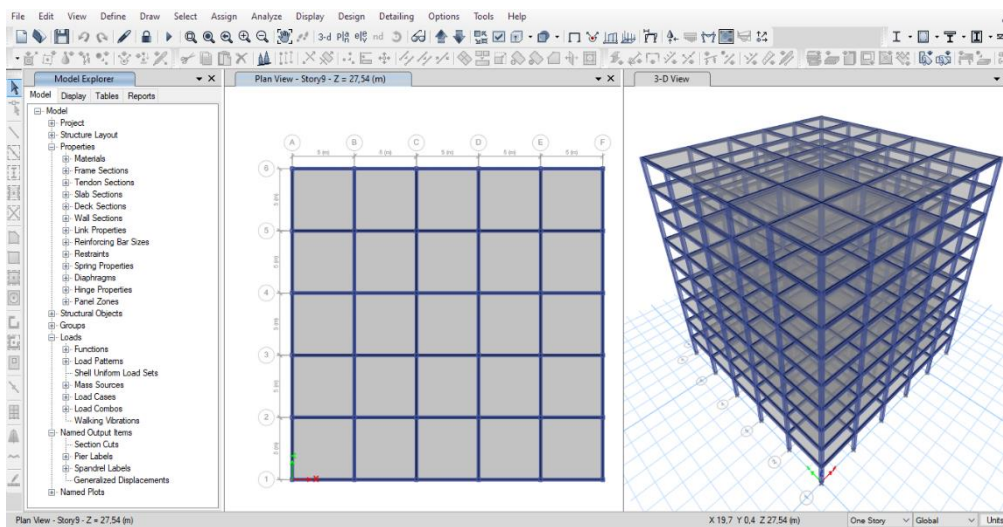


Fig 4.1. ETABS Interface: 3D Visualization of Structural Model [45].

4.2.1.2 Key Features Relevant to Seismic Analysis

Several key features of ETABS are crucial for performing seismic analysis of RC structures, particularly when simulating the effects of rehabilitation techniques and assessing post-rehabilitation performance.

- ∞ **Load Definitions and Application:** ETABS provides the ability to define various types of seismic loads, including:
 - ✚ **Lateral Loads:** Earthquake forces can be applied based on response spectrum or time-history analysis. Users can define lateral loads in both orthogonal directions to account for seismic activity in all possible directions.
 - ✚ **Seismic Load Combinations:** ETABS facilitates the combination of seismic loads with other load cases, such as dead loads, live loads, and wind loads, in compliance with building codes like ASCE 7, Eurocode, or local seismic regulations such as RPA 99/2003.
- ∞ **Nonlinear Material Models:** ETABS supports implementing advanced material models that capture the nonlinear behavior of materials under seismic loading. For concrete, the

software uses models such as the Concrete Damage Plasticity Model, which accounts for cracking, yielding, and damage accumulation. For steel reinforcement, ETABS uses a Bilinear Material Model that allows for the simulation of plastic deformation.

- ∞ **Performance-Based Seismic Design (PBD):** ETABS offers tools for integrating PBD principles, allowing engineers to assess a structure's performance under different seismic scenarios. This includes defining performance objectives such as Immediate Occupancy, Life Safety, and Collapse Prevention, which are critical for ensuring that a rehabilitated structure meets the required safety standards.
- ∞ **Post-Rehabilitation Modeling:** ETABS enables users to incorporate changes in material properties, geometry, and reinforcement details when modeling rehabilitated structures. This includes retrofitting strategies such as adding fiber-reinforced polymers (FRP) or shape-memory alloys (SMAs), improving RC structures' seismic resilience.
- ∞ **Seismic Performance Indicators:** Key seismic performance indicators can be extracted from the analysis, including:
 - ✚ **Displacement:** Maximum displacement at critical points in the structure, such as the roof or top floors.
 - ✚ **Drift:** The horizontal displacement relative to the structure's height is crucial for assessing potential damage and functionality after an earthquake.
 - ✚ **Inter-story Drift:** Lateral displacement between adjacent floors is a critical measure of structural deformation under seismic loading.

4.2.1.3 ETABS in Post-Rehabilitation Analysis

The ability to accurately model and evaluate the effects of rehabilitation techniques is one of the defining features of ETABS. The software allows for modifications to the original structural model, simulating various strengthening and retrofitting methods that are commonly employed to enhance the seismic performance of RC structures. These methods include:

- ✚ **FRP Wrapping:** Adding fiber-reinforced polymers to concrete beams, columns, and slabs enhances strength and ductility. ETABS can model these modifications by incorporating the material properties of FRPs into the analysis and evaluating the seismic performance of the rehabilitated structure.
- ✚ **SMAs for Seismic Resilience:** Using shape-memory alloys (SMAs) in structural rehabilitation can enhance the energy dissipation capacity of a structure. ETABS allows for the simulation of these materials and their impact on the overall seismic performance of the structure.

- ✚ **Base Isolation and Dampers:** ETABS can simulate the effects of base isolation systems and damping devices, which mitigate seismic forces by allowing controlled movement during an earthquake. These systems benefit rehabilitation projects, where the objective is to minimize damage to existing structures while improving their seismic resilience.

4.2.1.4 Case Studies and Applications

Several studies have demonstrated the effectiveness of ETABS in seismic analysis and rehabilitation, such as those by Hsiao et al. [46] explored the development and testing of naturally buckling steel braces in seismic rehabilitation. The study utilized ETABS to model and simulate the behavior of buildings with buckling braces, highlighting the software's ability to accurately simulate the seismic response of structures with advanced damping systems. The findings underscored the importance of buckling braces in enhancing the resilience of RC structures during seismic events—another study by Belbachir et al. [47] explored an innovative base isolation technique to enhance the seismic response of residential RC buildings. The study demonstrated using ETABS to model and simulate the improved seismic performance of buildings retrofitted with this novel base isolation system. The results showed significant improvements in the structure's response to seismic forces, highlighting the effectiveness of ETABS in evaluating the impact of innovative rehabilitation techniques—furthermore, Bakhouché et al. [48] investigated the nonlinear behavior of irregularly shaped reinforced concrete buildings with different X-bracing positions using ETABS. The study emphasized the importance of accurately modeling complex geometries and bracing configurations in predicting the seismic behavior of irregular buildings. It found that the position and configuration of X-bracing systems significantly impacted the building's seismic response, highlighting the need for precise modeling in ETABS to capture the effects of such irregularities on the overall structural performance.

4.2.2 Material Laws in ETABS

The accuracy of a numerical simulation depends heavily on the material models used to represent the structural components. In ETABS, a range of material models is available to simulate the behavior of reinforced concrete, steel reinforcement, and advanced materials. These models are essential for evaluating the real-world behavior of RC structures under seismic loading.

4.2.2.1 Concrete Material Models in ETABS

ETABS includes several material models for concrete, each suited to different types of loading conditions and structural responses. These models are essential for capturing the nonlinear

behavior of concrete under seismic loading, including cracking, crushing, and post-cracking softening.

A. Concrete Damage Plasticity (CDP) Model:

The Concrete Damage Plasticity (CDP) model in ETABS is the most advanced and widely used model for simulating the nonlinear behavior of concrete under dynamic loads, particularly seismic forces. It is particularly effective for simulating concrete's damage under both tensile cracking and compressive crushing, which are critical for understanding concrete's post-cracking and post-failure behavior.

Key Features of the CDP Model:

- ✚ **Tensile Cracking:** The model accounts for the formation of cracks under tensile stress. As concrete is very weak in tension, it will crack when the tensile strength is exceeded.
- ✚ **Compressive Crushing:** The model also captures the behavior of concrete under high compressive stresses, which causes it to crush.
- ✚ **Damage Evolution:** The model simulates how concrete degrades and loses stiffness as cracks and plastic deformations accumulate under loading. This degradation is crucial for simulating the performance of concrete structures during and after seismic events.

Model Parameters:

- ✚ **Compressive Yield Surface:** This defines the limit at which concrete begins to crush under high compressive stress.
- ✚ **Tensile Yield Surface:** This defines the tensile strength limit at which cracks form in the material.
- ✚ **Damage Parameters:** These parameters quantify the evolution of damage due to cracking and crushing. Typically, a dilation angle defines the transition from elastic to plastic behavior.
- ✚ **Poisson's Ratio and Elastic Modulus:** These properties are used to define the linear elastic portion of the concrete behavior before yielding. Typical values are:
 - * **Poisson's Ratio:** 0.2 for standard concrete.
 - * **Elastic Modulus:** 25,000–35,000 MPa, depending on the concrete mix and type.

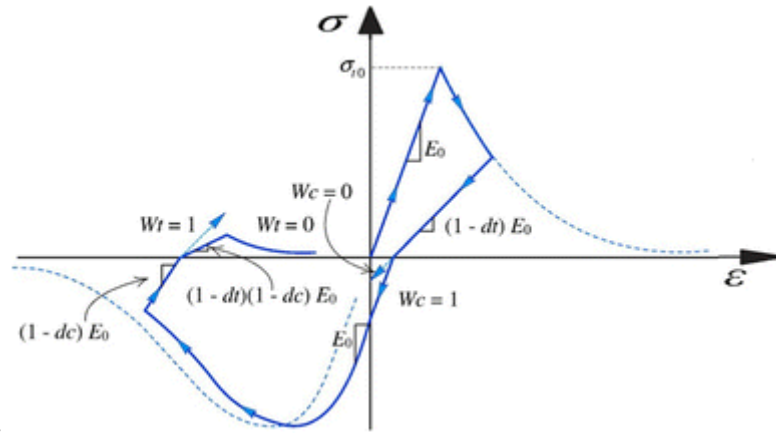


Fig 4.2. Tensile and compressive damage indexes in the CDP model[49].

B. Hognestad's Parabola Model

Hognestad's Parabola model is a simplified approach for representing concrete's stress-strain behavior in compression, particularly when the material remains in the elastic range. It is often used in cases where a detailed nonlinear analysis is not required.

Key Features of the Hognestad's Model:

- ✚ **Stress-Strain Relationship:** The model provides a parabolic curve for compressive stress-strain behavior, which is typically used for concrete under low to moderate stress conditions. This model is particularly useful for reinforced concrete beams under flexural loading, where the concrete stays within the elastic region for most of the load duration.

Parameters:

- ✚ **Compressive Strength:** The maximum stress that concrete can withstand before crushing.
- ✚ **Strain at Peak Stress:** The strain corresponding to the maximum compressive stress.
- ✚ **Strain Hardening:** A small post-peak strain hardening can be included, though this model assumes that the material fails immediately after peak stress.

Equation for Stress-Strain Curve:

A parabolic function gives the stress-strain relationship:

$$\sigma_c = f'_c \left[2 \frac{\epsilon_c}{\epsilon_0} - \left(\frac{\epsilon_c}{\epsilon_0} \right)^2 \right] \quad (4.1)$$

$$\epsilon_0 = \frac{2f'_c}{E_c} \quad (4.2)$$

Where:

- σ_c Compressive stress,
- E_c modulus of elasticity of concrete (MPa)

- f'_c maximum compressive strength of concrete (the unconfined cylinder specimen) (MPa),
- ϵ_c nominal compressive strain in concrete,
- ϵ_0 Strain at maximum stress (the strain at the curve's peak point)

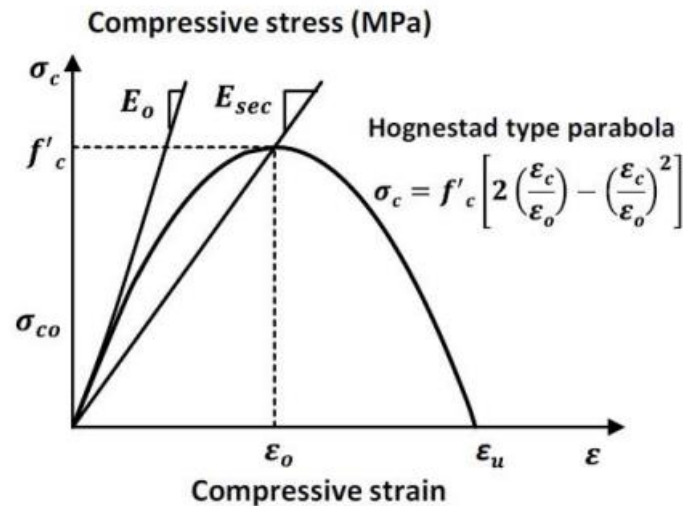


Fig 4.3. Stress-Strain Curve for Concrete Compression Based on Hognestad's Model[50].

C. Linear Elastic Model

The Linear Elastic Model is the simplest material model used in ETABS and is generally applied to concrete under low-load conditions or for preliminary structural analysis. It assumes that concrete behaves elastically without plastic deformation, cracking, or crushing.

Key Features of the Linear Elastic Model:

- ✚ **Elastic Behavior:** The material follows Hooke's Law, where stress is proportional to strain.
- ✚ **No Cracking or Crushing:** The model does not account for any damage, cracking, or failure, making it suitable for initial loading conditions where material failure is unexpected.
- ✚ **Simple Stress-Strain Relationship:** Concrete behaves as a homogeneous elastic material, defined by a constant modulus of elasticity and Poisson's ratio.

Parameters:

- ✚ **Modulus of Elasticity (E):** Typically, in the range of 25,000–35,000 MPa for normal-strength concrete.
- ✚ **Poisson's Ratio (ν):** Typically, around 0.2, representing the ratio of lateral strain to axial strain under compression.

This model is primarily used in linear static analyses, where the material does not undergo large deformations or nonlinear behavior.

D. Mander Model:

The Mander model enhances the compressive strength of concrete through confined reinforcement, simulating the increase in ductility and strength when concrete is confined by steel spirals or hoops. It is often used for circular and square sections under compression.

Applications: Used in bridge piers, seismic-resistant columns, and concrete beams.

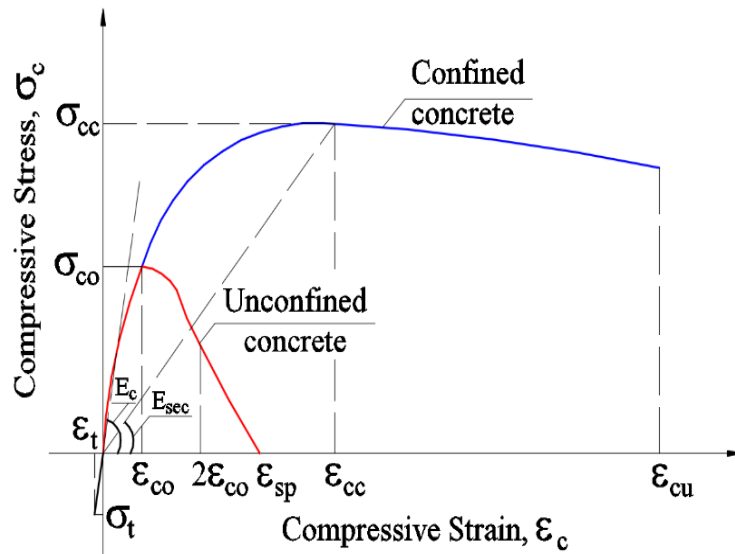


Fig 4.4. Mander Model for Confined Concrete[51].

E. Kent-Park Model:

The Kent-Park model combines confinement effects with tension stiffening, accounting for both compressive and tensile forces in concrete. This is useful for simulating the flexural behavior of concrete structures.

Applications: Ideal for reinforced concrete beams and slabs under bending loads.

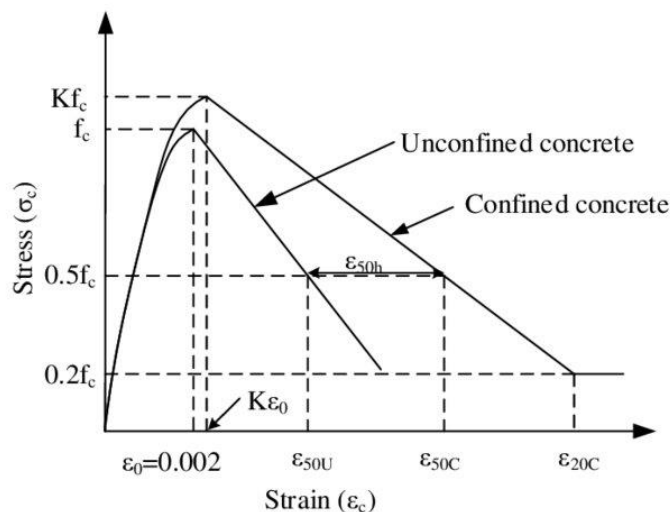


Fig 4.5. Kent and Park model for confined and unconfined concrete.

F. FIB Model:

The FIB Model offers a comprehensive constitutive model for concrete, encompassing cracking, crushing, tension stiffening, and cyclic loading. It is adaptable to various loading scenarios and concrete types.

Applications: Suitable for complex structural analysis and research studies.

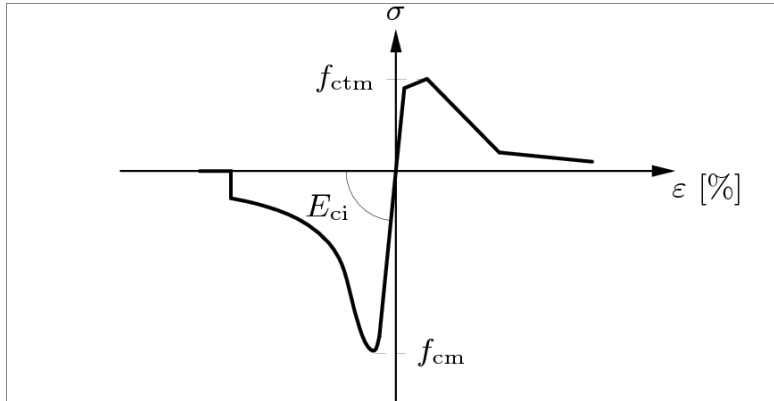


Fig 4.6. Stress-strain diagram according to fib Model Code for Concrete Structures.

4.2.2.2 Steel Material Models in ETABS

Steel reinforcement plays a critical role in the behavior of reinforced concrete (RC) structures, particularly under seismic loading. ETABS provides several material models to simulate steel reinforcement behavior in concrete structures accurately, especially when considering the nonlinear effects during cyclic loading and plastic deformations. This section explores the different steel material models available in ETABS, their key features, and the conditions under which they must be applied.

A. Elastic-Perfectly Plastic Model

The Elastic-Perfectly Plastic Model is one of the most commonly used models in ETABS to represent steel reinforcement. It is a relatively simple model that assumes elastic behavior up to the yield stress and perfectly plastic behavior thereafter, with no strain hardening.

Key Features:

- ✚ Elastic Behavior:** Steel behaves elastically up to the yield stress, meaning stress is proportional to strain.
- ✚ Perfectly Plastic:** After reaching the yield point, the material deforms plastically with no additional increase in stress, which represents the plateau in the stress-strain curve for steel.
- ✚ No Strain Hardening:** The model assumes that once steel yields, it does not undergo further hardening, which simplifies the analysis.

Parameters:

- ✚ **Yield Stress:** Defines the stress at which steel transitions from elastic to plastic behavior. Common values for yield stress are 400-500 MPa for standard reinforcement steel grades.
- ✚ **Ultimate Strength:** Steel's ultimate strength, which may be higher than the yield stress, though the Elastic-Perfectly Plastic model does not account for strain hardening beyond the yield point.
- ✚ **Modulus of Elasticity:** Typically, 200,000 MPa for steel, reflecting its high stiffness.
- ✚ **Poisson's Ratio:** Usually around 0.3 for steel.

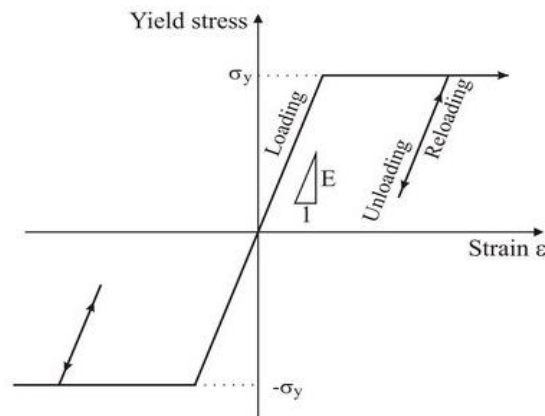


Fig 4.7. Elastic-Perfectly Plastic Stress-Strain Curve for Steel[52].

B. Bilinear Material Model (Strain Hardening)

The Bilinear Material Model extends the Elastic-Perfectly Plastic model by including strain hardening in the post-yield region. This model assumes that after yielding, the material exhibits an additional increase in strength due to strain hardening, with a defined slope for the post-yield behavior.

Key Features:

- ✚ **Strain Hardening:** After the yield point, the material exhibits strain hardening, which means that the steel continues to increase its strength as it deforms.
- ✚ **Bilinear Stress-Strain Curve:** The curve has two distinct linear segments—one for elastic behavior and one for plastic, with a defined slope for the hardening region.

Parameters:

- ✚ **Yield Strength:** Defined as in the Elastic-Perfectly Plastic model.
- ✚ **Strain Hardening Modulus:** Represents the slope of the post-yield curve and determines how much strength the material gains after yielding.
- ✚ **Ultimate Strength:** Represents the maximum stress that steel can withstand before failure.

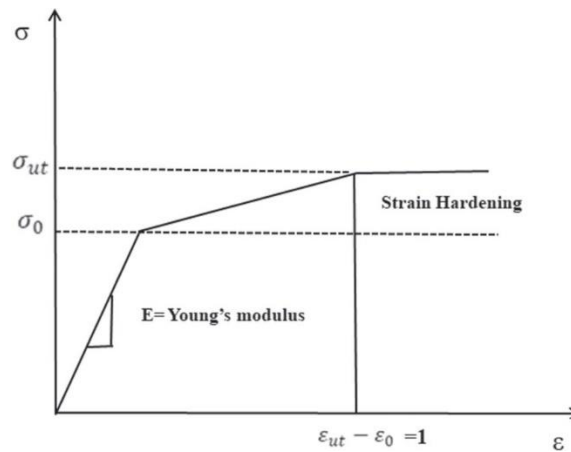


Fig 4.8. Bilinear Stress-Strain Curve with Strain Hardening for Steel [53].

C. Multilinear Model

The Multilinear Model is a more advanced representation of steel's stress-strain behavior. It can simulate the nonlinear strain hardening and softening that steel undergoes during large deformations, particularly under cyclic loading. This model is often used for highly detailed analysis where large inelastic deformations are expected.

Key Features:

- ✚ **Multiple Yield Points:** Unlike the bilinear model, the multilinear model can account for multiple yield points and varying post-yield behavior, including softening and strain hardening.
- ✚ **Accurate for Large Deformations:** It is used in situations where the material undergoes large, irreversible deformations, such as in plastic hinges during seismic loading.
- ✚ **Incorporation of Stress-Strain Data:** This model uses detailed experimental stress-strain data for steel to accurately represent its behavior.

Parameters:

- ✚ **Stress-strain curve Segments:** The model uses experimental or material-specific data to define multiple stress-strain segments.
- ✚ **Post-Yield Behavior:** Can capture softening, strain hardening, and unloading/reloading behavior under cyclic loads.

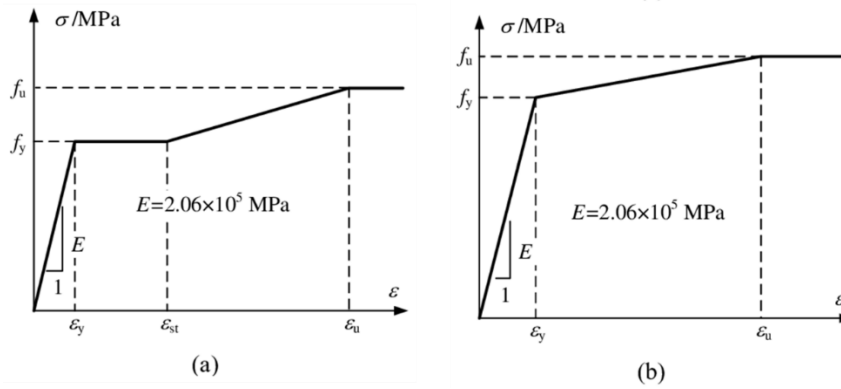


Fig 4.9. Stress-Strain Curves for Steel Representing the Multilinear Material Model [54].

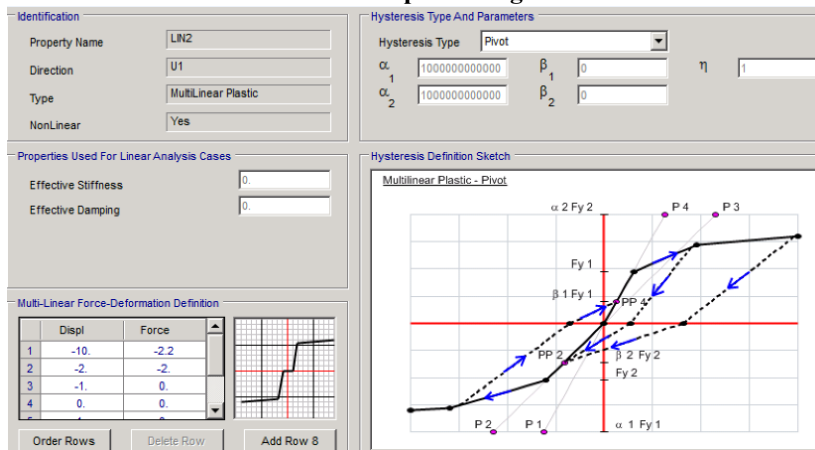


Fig 4.10. Multilinear Plasticity model showing strain hardening and softening using the pivot hysteresis method [55].

4.2.3 Nonlinear Behavior in ETABS

4.2.3.1 Material Nonlinearity in ETABS

Material nonlinearity in ETABS is a critical feature that allows for accurate modeling of the inelastic behavior of reinforced concrete (RC) structures. This involves capturing how concrete and steel react under extreme loads, including cracking, crushing, yielding, and strain hardening. By leveraging advanced material models, ETABS ensures that structural performance under seismic loads is realistically simulated.

A. Nonlinear Stress-Strain Relationships for Concrete

The nonlinear stress-strain behavior of concrete in ETABS encompasses a range of models designed to accurately simulate the material's performance under seismic and other extreme loads. These models capture critical phenomena such as cracking, crushing, and post-cracking degradation. The models include:

- **Comprehensive Models:** Advanced nonlinear models, such as the Concrete Plasticity Damage (CPD) and the FIB Model, account for cyclic degradation and energy dissipation, making them suitable for detailed seismic studies.

- **Simplified Approaches:** Models like Hognestad's Parabola provide practical approximations for linear and moderate nonlinear conditions, ideal for preliminary analysis or structural components under low stress.
- **Confined Concrete Effects:** Models such as the Mander Model and the Kent-Park Model incorporate the influence of lateral confinement, simulating enhanced compressive strength and ductility.

This study applied these models based on the structural demands and analysis objectives, ensuring a robust representation of concrete behavior under static and dynamic loading conditions.

B. Nonlinear Stress-Strain Relationships for Steel

The behavior of steel reinforcement under seismic loads is represented using several material models in ETABS, capturing key features like elastic-plastic transitions, strain hardening, and cyclic degradation:

- **Simplified Models:** The Elastic-Perfectly Plastic (EPP) model is a foundational approach that efficiently models steel's behavior up to yielding and plastic deformation.
- **Enhanced Strain Hardening:** The Bilinear Model extends the EPP model by including post-yield strain hardening for increased accuracy in predicting inelastic deformations.
- **Detailed Multilinear Models:** These provide the most realistic steel representation under seismic loads, including cyclic loading effects, softening, and unloading/reloading behaviors.

As implemented in the structural analysis, these models form the core of the material definitions for plastic hinges and inelastic deformations.

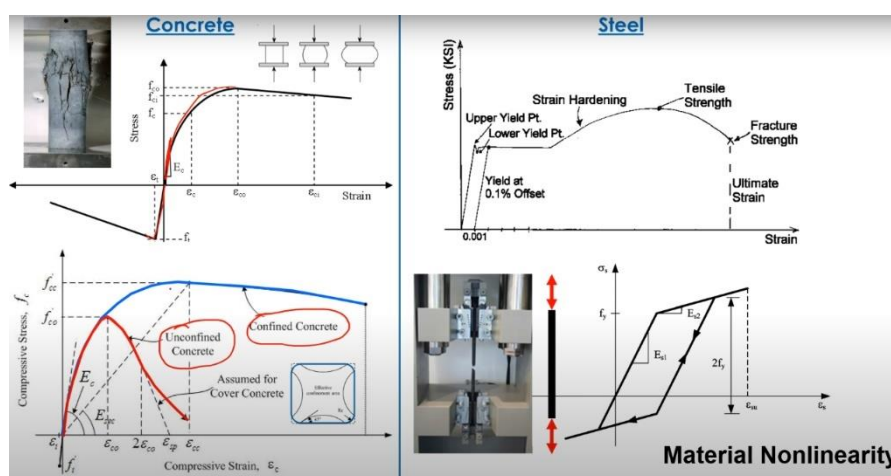


Fig 4.11. Stress-Strain Behavior and Nonlinearity of Concrete and Steel.

C. Plastic Hinge Modeling for RC Elements in ETABS

Plastic hinges are critical for simulating the inelastic behavior of RC elements under seismic loads. They represent regions of the structure where significant plastic deformation occurs, often at:

- Beam and column end, Midpoints of braces and wall boundaries.

In ETABS, plastic hinges are characterized by:

- Moment-Rotation Relationships for beams and columns, Axial Load-Deformation Relationships for braces, Shear Force-Displacement Relationships for walls.

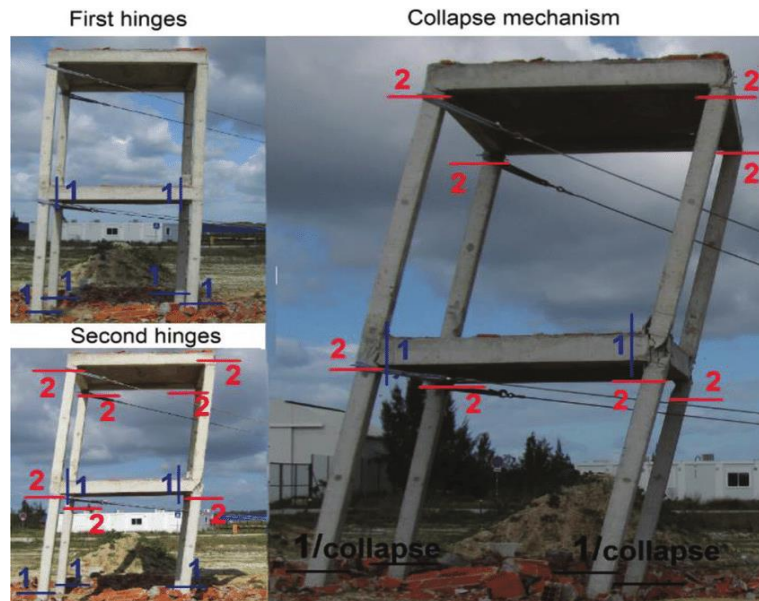


Fig 4.12. Progression of Plastic Hinges and Collapse Mechanism in a Reinforced Concrete Frame Under Lateral Loading [56].

∞ Plastic Hinge Types

ETABS offers both pre-defined and user-defined hinge properties:

- **Pre-Defined Hinges:**

Based on standards like FEMA 356, ASCE 41-17, or other design codes. Typical hinge types include:

- ✚ M3 (Moment about the central axis).
- ✚ V2 (Shear along the minor axis).
- ✚ P (Axial force).

- **User-defined hinges:**

- ✚ Custom hinges were created using stress-strain data from material models.
- ✚ Requires input of plastic behavior parameters (e.g., yield points, ultimate strength).

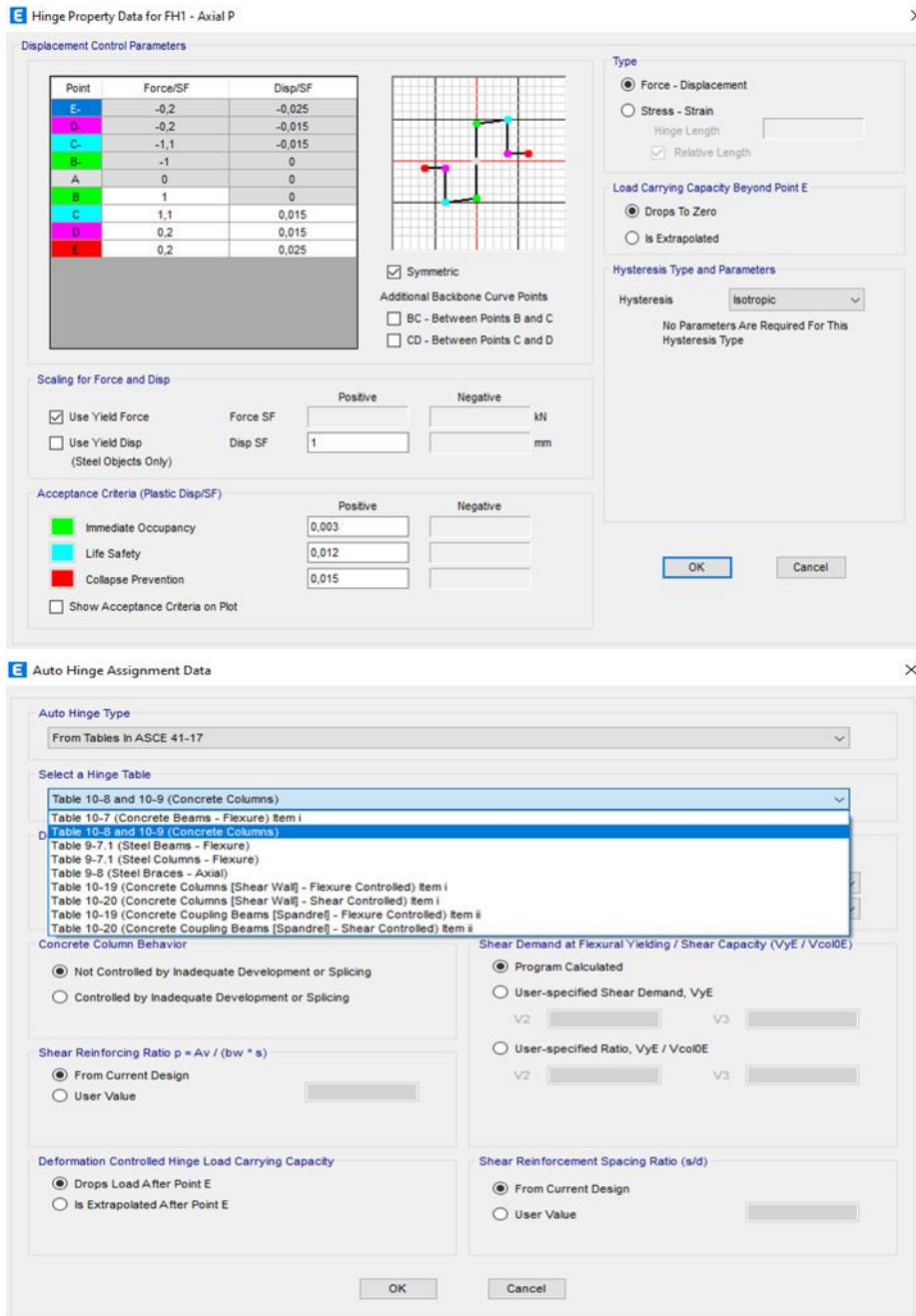


Fig 4.13. Plastic Hinge Definition and Assignment in ETABS.

∞ Implementation in ETABS

- Assigning Hinges

Beam Elements:

- ✚ Hinges are placed at both ends, capturing the moment-rotation behavior.
- ✚ Typical hinge types: M3 (bending) and V2 (shear).

Column Elements:

- ✚ Hinges are placed at ends, considering P-M Interaction (Axial force and Moment).
- ✚ Typical hinge types: P-M2-M3 (Axial and biaxial moment interaction).

Wall Elements:

- ✚ Hinges are assigned to capture shear deformation and flexural rotation.
- ✚ Common hinge types: V2 (Shear) and M3 (Flexural).

Braces:

- ✚ Hinges model axial deformation (tension and compression).
- ✚ Typical hinge type: P (Axial force).

∞ **Plastic Hinge Properties in ETABS**

- **Length of Hinges:**

- ✚ Hinges are assumed to occupy a finite element length, typically defined as a fraction of the element length (e.g., 0.1L to 0.9L).

- **Hinge Data Table:**

ETABS provides a table for input or review of hinge parameters, including:

- ✚ Yield moments, ultimate moments.
- ✚ Plastic rotation limits θ_y, θ_u

4.2.3.2 Geometric Nonlinearity in ETABS

Geometric nonlinearity refers to the phenomenon where the geometry of a structure changes during deformation, affecting the structure’s stiffness matrix and overall behavior. This occurs when large displacements or rotations lead to nonlinear changes in the structural system’s response. Unlike material nonlinearity, which deals with how a material's properties change under stress or strain, geometric nonlinearity is concerned with the shape or configuration changes of the structure itself, affecting the internal forces, moments, and overall stability.

In ETABS, geometric nonlinearities are handled through advanced methods such as P-Delta effects, large deflections, and stress stiffening. These models are crucial for accurately simulating the response of structures under extreme conditions like seismic loading, where significant displacements occur.

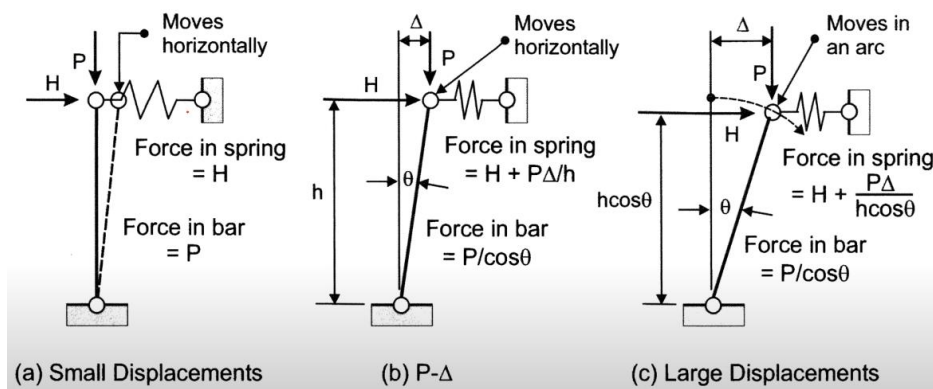


Fig 4.14. Geometric Nonlinearity.

A. P-Delta Effects

P-Delta effects (also called P- Δ effects) are a form of geometric nonlinearity observed when large displacements influence the internal forces of the structure. This is particularly important in tall, slender structures like columns or frames, where the lateral displacement due to seismic loading generates additional moments that amplify the structure's bending.

- ✚ When a structure such as a tall column is subjected to an axial load (P), the displacement caused by the axial load can lead to a secondary moment (Δ). As the structure bends, the applied load (P) acts on the displaced structure, creating an additional moment that further amplifies the displacement, making it more significant than in linear analysis.
- ✚ ETABS includes P-Delta effects in its second-order analysis, allowing the software to adjust the stiffness matrix during the analysis to account for the changing geometry due to large displacements. This leads to a more accurate prediction of the structure's behavior under seismic and other extreme loads.

B. Large Deflections

Large deflections occur when structures undergo significant displacements, causing the original geometry to change and, consequently, altering the internal forces and moments. Unlike small deflections, where the relationship between load and displacement is linear, large deflections introduce a nonlinear response, meaning that the displacement itself impacts the overall behavior of the structure.

- ✚ Large Deflection Behavior: Consider a cantilever beam subjected to a substantial load. As the beam bends, its displacement angle alters, affecting the moment distribution and internal forces. This leads to an altered stiffness matrix, which must be updated during each analysis step to account for the large deflections.
- ✚ ETABS can model large deflections in both static and dynamic analyses. It continuously updates the displacement and geometry at each load increment, ensuring that the deformed configuration of the structure is taken into account, which improves the accuracy of stress and strain predictions.

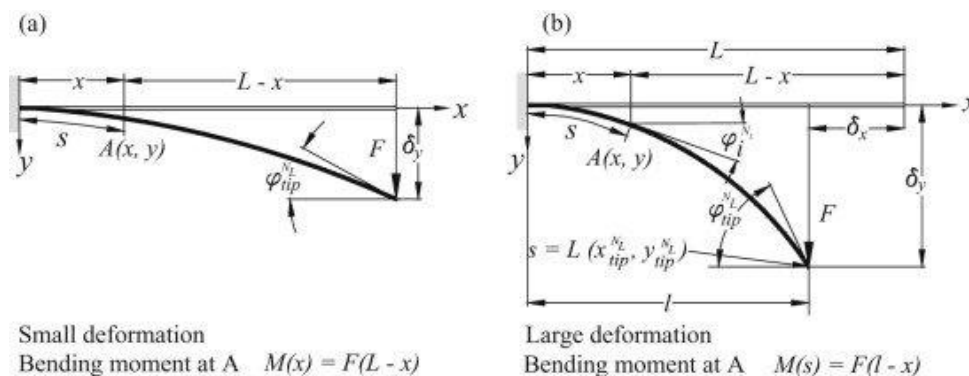


Fig 4.15. (a) Small deformation and (b) large deformation of a cantilever beam [57].

4.2.4 Application of Advanced Seismic Assessment Techniques in ETABS

4.2.4.1 Nonlinear Static Analysis (Pushover Analysis)

Nonlinear static (pushover) analysis is a widely used technique to assess the inelastic seismic performance of structures under gradually increasing lateral forces. Unlike linear analysis, which assumes elastic behavior, pushover analysis captures plastic deformations, hinge formation, and progressive failure mechanisms, making it a reliable tool for performance-based seismic design.

A. Purpose and Relevance

Pushover analysis provides critical insights into:

- Plastic behavior of elements (yielding, cracking, hinge formation).
- Energy dissipation capacity and retrofitting effectiveness (e.g., FRP, SMA).
- Displacements, drifts, and failure mechanisms under seismic loading.

It is particularly valuable for evaluating retrofitted structures and ensuring compliance with performance objectives: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

B. Procedure of Nonlinear Static (Pushover) Analysis

Modeling in ETABS: Define geometry, materials (concrete, reinforcement, retrofit), and boundary conditions.

Application of Lateral Loads: Incremental horizontal forces simulate seismic effects. Common patterns include:

i. Uniform Load Distribution

The lateral load is applied evenly across the structure's height in uniform load distribution. This load pattern assumes that the seismic forces act uniformly on each story of the building.

✚ This pattern is often used for low-rise buildings or buildings with regular configurations and symmetrical mass distribution. For such buildings, the seismic forces at each floor are assumed to be equally distributed.

✚ This load pattern type may not capture higher buildings' more realistic dynamic effects, but it simplifies the analysis. It is often used for initial screening or buildings in low seismic zones.

✚ Load Application:

Lateral forces are evenly distributed across all levels.

Each floor receives an equal share of the total base shear, calculated as:

$$F_i = \frac{V_b}{n} \quad (4.6)$$

Where:

V_b : Total base shear

n : Total number of floors

F_i : Lateral force at the i th floor

✚ Code Recommendations

- **Eurocode 8:** Suggests using uniform lateral force distribution for low-rise or regular buildings as part of the equivalent static force method.
- **ATC-40:** Recommends uniform loads for initial evaluations, particularly for structures with simple configurations.
- **FEMA 356:** Allows uniform load distribution for quick assessments and buildings with evenly distributed mass and stiffness.

ii. Triangular Load Distribution

In triangular load distribution, the applied lateral load increases linearly from the bottom to the top of the structure. This means the lateral force at the top floors is more significant than that at the lower floors, which is more reflective of real seismic behavior.

✚ Eurocode 8 and FEMA 356 both recommend the triangular load pattern for buildings with taller or irregular shapes, as they more accurately represent the distribution of forces during an earthquake.

✚ This pattern assumes that higher floors experience greater inertial forces due to their greater mass and relative displacement during an earthquake.

✚ Triangular distribution is typically used for buildings with non-uniform mass or higher stories, as it captures the realistic effects of a building's higher levels of seismic demand.

✚ **Load Application**

Lateral forces are distributed proportionally to the height of each floor, with the highest forces applied at the roof level. The force at each level is calculated as:

$$F_i = V_b \cdot \frac{h_i}{\sum h_j} \quad (4.7)$$

Where:

h_i : Height of the i th floor above the base

$\sum h_j$: Total height of the building

F_i : Lateral force at the i th floor

iii. Load Distribution Following Vibration Modes

This method involves applying lateral loads based on the vibration modes of the structure, as determined by a modal analysis. Each mode shape represents a specific deformation pattern, and the forces are distributed to reflect the structure's dynamic response.

✚ **Eurocode 8:** Strongly recommends modal load distributions for irregular buildings or those dominated by higher modes.

✚ **ATC-40:** Advocates for modal pushover analysis to capture the effects of torsion, irregularities, and higher modes.

✚ **FEMA 356:** Specifies modal load distribution for complex or tall structures, particularly in performance-based design evaluations.

✚ **Justification**

- Provides the most realistic representation of seismic forces by incorporating the building's dynamic characteristics.
- Essential for irregular buildings, tall structures, or cases where higher vibration modes significantly influence the response.

✚ **Load Application**

- Perform a modal analysis to determine the structure's natural frequencies and mode shapes.
- Select the dominant vibration modes (typically the first few modes based on participation factors).
- Distribute lateral forces according to the amplitude of the mode shapes, scaled to match the base shear:

$$F_i^{(m)} = V_b^{(m)} \cdot \phi_i^{(m)} \quad (4.8)$$

Where:

$F_i^{(m)}$: Lateral force at the *i*th floor for mode *m*

$\phi_i^{(m)}$: Mode shape amplitude at the *i*th floor for mode *m*

$V_b^{(m)}$: Base shear for mode *m*

- Combine modal responses using methods such as:

Square Root of the Sum of Squares (SRSS): For independent modes.

Complete Quadratic Combination (CQC): For closely spaced modes.

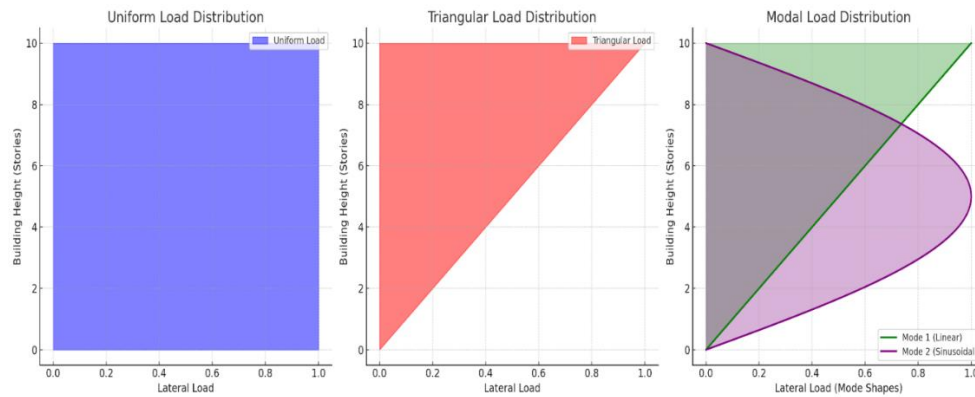


Fig 4.16. Comparative Visualizations of Lateral Load Distributions for Pushover Analysis.

Incremental Loading

- ∞ **Incremental Load Application:** The lateral force is incrementally increased in small steps, allowing the software to track the deformation of the structure at each step. The incremental steps help capture the transition from elastic to inelastic behavior.
- ∞ **Displacement Tracking:** As the load increases, the roof level or top floor displacement is monitored. This allows tracking when the structure begins to experience plastic deformation and plastic hinge formation.

Define Performance Levels

Track the transition from elastic range → yielding → plastic range.

Identify Plastic Hinges and Damage Locations

- ∞ **Plastic Hinge Formation:** ETABS identifies where plastic hinges develop (beams or columns), marking the onset of yielding and plastic deformation.
- ∞ **Damage Assessment:** Critical damage zones are highlighted, such as areas of excessive cracking, concrete crushing, or steel yielding.

Determination of Seismic Demand

Seismic demand reflects the forces and displacements a structure endures during an earthquake, typically obtained from response spectrum or time-history analyses. In Algeria, the elastic response spectrum of RPA 99 (2003) is used, but for performance-based evaluation it is converted into a Displacement-Acceleration Response Spectrum (ADRS) to better capture deformations.

$$\text{The spectral displacement is calculated as: } S_{de} = \frac{T_i^2}{4\pi^2} \cdot S_{ae} \quad (4.9)$$

Where: S_{de} : Spectral Displacement, S_{ae} : Spectral Acceleration, T: The fundamental period of the structure.

The ADRS method links acceleration and displacement, incorporating mode shapes and damping, thus providing a more realistic prediction of structural performance under seismic loading.

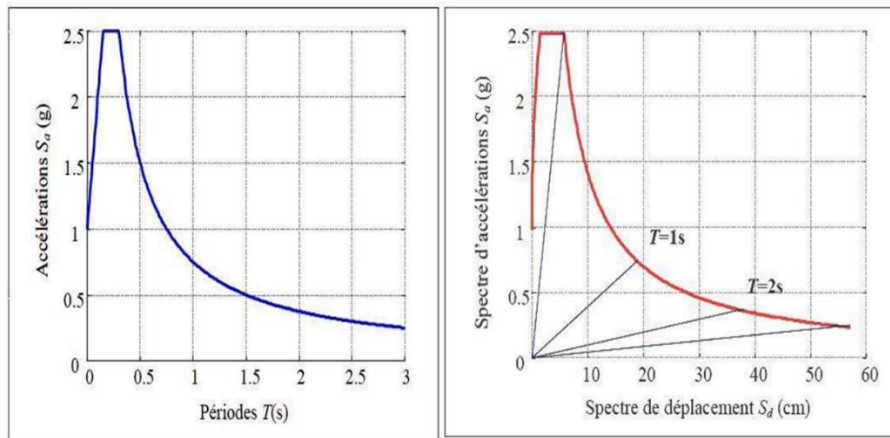


Fig. 4.17. Seismic Demand Determination Using ADRS [58].

Step 01. Determination of the Capacity Curve (Push-Over Curve)

The capacity curve (also known as the pushover curve) is plotted to show the relationship between base shear and displacement at the top of the structure, this curve allows engineers to visualize how the structure will behave under progressively increasing seismic forces, and it provides critical information regarding the ultimate capacity of the structure.

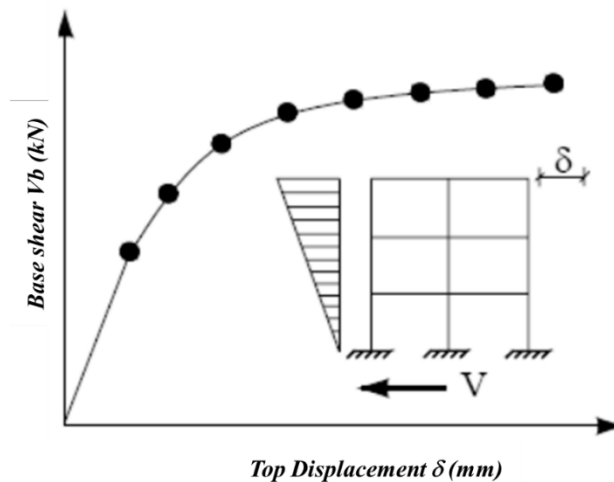


Fig. 4.18. Capacity Curve (Push-over) of a Structure.

Step 02. Interpretation of Pushover Results:

❖ **Performance Points**

A critical outcome of the pushover analysis is the performance point, which represents the intersection of the demand spectrum (earthquake loading) and the capacity curve. This point indicates:

- The maximum displacement the structure can undergo without significant risk of failure.
- The structure's base shear can be sustained before collapse or a performance limit.

❖ **Performance Levels (as per seismic design codes)**

The capacity curve can be evaluated using performance-based design (PBD) criteria to categorize the seismic performance of the structure into various levels:

- **Immediate Occupancy (IO):** The building can be occupied after an earthquake with only minor repairs.
- **Life Safety (LS):** The structure is stable and can ensure life safety, but repairs are needed before occupancy.
- **Collapse Prevention (CP):** The structure is close to collapse, and further use is prohibited.

❖ **Damage Assessment**

As the pushover analysis progresses, engineers can track the damage progression within the structure:

- The location of plastic hinges (both in beams and columns).
- Nonlinear deformations and the extent to which these deformations are within acceptable limits.

This allows for a detailed understanding of the seismic vulnerabilities of the structure.

4.2.4.2 Nonlinear Dynamic Analysis

Nonlinear dynamic (time-history) analysis evaluates the seismic response of structures under real or synthetic ground motions. Unlike pushover or simplified methods, it captures time-dependent inelastic behavior, making it essential for RC structures and for validating retrofitting techniques. Key Features Compared to Static Analysis

- Includes dynamic inertia effects and higher modes.
- Models' energy dissipation via damping and hysteresis.
- Accounts for material and geometric nonlinearities.

A. Fundamental Nonlinearities

- **Geometric Nonlinearity:** Large displacements and rotations (P- Δ effects), captured in ETABS through geometric stiffness updates.
- **Material Nonlinearity:**
 - ∞ **Concrete:** Cracking, crushing, stiffness degradation.
 - ∞ **Steel:** Yielding, strain hardening, cyclic degradation.

B. Seismic Input

- **Ground Motions:** Either recorded (from Algerian or similar regions) or synthetic (compatible with RPA 99/2003).

- **Scaling & Spectral Matching:** Adjusted to match design spectra (PGA, duration, site effects).

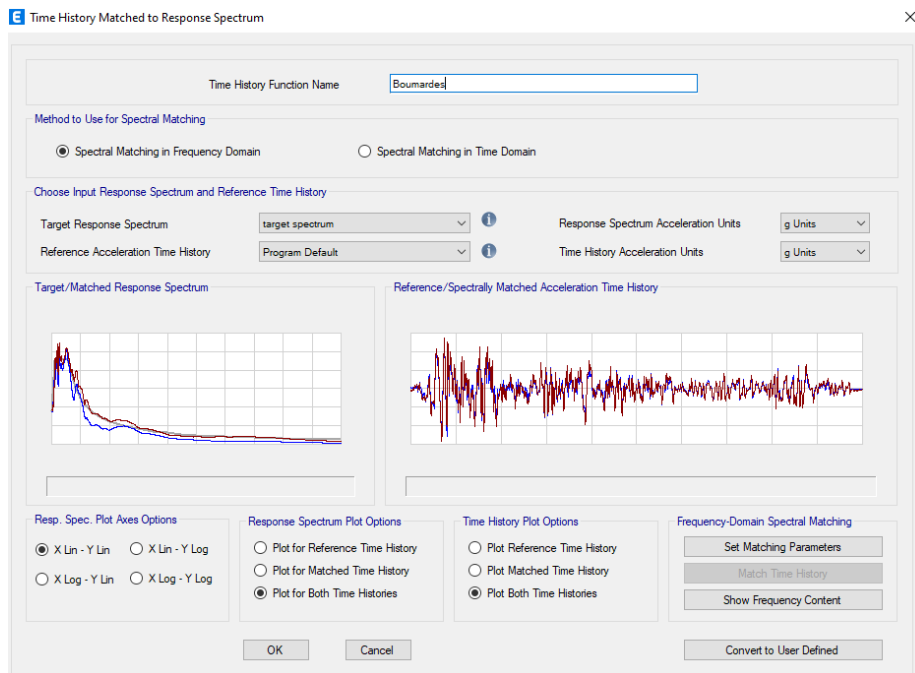


Fig 4.19. Time-History Spectral Matching Process in ETABS.

C. Mathematical Framework for Dynamic Analysis

∞ Equation of Motion

The equation of motion for a multi-degree-of-freedom system under seismic loading is:

$$M\ddot{U} + C\dot{U} + KU = F(t) \quad (4.10)$$

Where:

M, C, K : Mass, damping, and stiffness matrices.

\ddot{U}, \dot{U}, U : Displacement, velocity, and acceleration vectors.

$F(t)$: Time-dependent seismic forces.

∞ Incremental Dynamic Equilibrium

The incremental form of the equation accounts for nonlinear stiffness and damping:

$$M\Delta\ddot{U} + C\Delta\dot{U} + K_t\Delta U = R_{ext} - R_{int} \quad (4.11)$$

Where:

K_t : Tangent stiffness matrix, updated iteratively.

R_{ext} : External forces (Seismic).

R_{int} : Internal resisting forces.

C. Numerical Integration Techniques

∞ Explicit Methods

Central Difference Method:

- Solves the equation of motion by directly computing displacements at each time step.

- Equation:

$$u_{t+\Delta t} = 2U_t - U_{t-\Delta t} + \Delta t^2 M^{-1} (F_t - KU_t) \quad (4.12)$$

- **Pros:** Simple and computationally efficient.
- **Cons:** Conditionally stable, requiring small time steps.

∞ **Implicit Methods**

Newmark-Beta Method:

- Combines displacement and velocity updates for unconditional stability.

- Equations:

$$U_{t+\Delta t} = U_t + \Delta t \dot{U}_t + \frac{\Delta t^2}{2} (1 - \beta) \ddot{U}_t + \beta \Delta t^2 \ddot{U}_{t+\Delta t} \quad (4.13)$$

$$\dot{U}_{t+\Delta t} = \dot{U}_t + \Delta t (1 - \gamma) \ddot{U}_t + \gamma \Delta t \ddot{U}_{t+\Delta t} \quad (4.14)$$

- Parameters β and γ are chosen to balance accuracy and stability.

- Typical Coefficient Values:

$\gamma=0.5, \beta=0.25$: For average acceleration (unconditionally stable).

$\gamma=0.6, \beta=0.3025$: For more damping in high-frequency modes.

- Applications:

Newmark-Beta is suitable for general structural dynamic problems, including seismic analyses.

Wilson-Theta Method

- The Wilson-Theta method modifies the standard Newmark method to enhance stability for systems with high stiffness.

- Equation:

$$\ddot{U}_{t+\theta\Delta t} = \frac{1}{\theta\Delta t} (F_{t+\theta\Delta t} - F_t) \quad (4.15)$$

Where:

$\theta > 1$ ensures stability.

- Typical Coefficient Values:

$\theta=1.37$: Recommended for unconditional stability.

- Applications:

Ideal for stiff systems or when higher accuracy is needed for responses at small time steps.

Collocation Method

- The Collocation method evaluates the response at intermediate points within a time step to improve accuracy.

- Collocation Points: Represent intermediate points in the time step where the equations of motion are evaluated.
- Coefficients depend on system-specific parameters, including modal frequencies and damping ratios. Calibration is essential for accuracy.

- Equation:

$$U_{t+\Delta t} = U_t + \int_t^{t+\Delta t} \dot{U}(s) ds \quad (4.16)$$

- The method uses weights for interpolation within the time step.
- Typical Coefficients:
Requires system-specific calibration based on modal frequencies and damping ratios.
- Applications:
Used in precision modeling for systems with strong modal coupling.

Hilber-Hughes-Taylor (HHT) Method

- The HHT method introduces a damping parameter α to control high-frequency response oscillations.

- Equations:

$$M(\alpha \ddot{U}_{t+\Delta t} + (1 - \alpha) \ddot{U}_t) + C(\alpha \dot{U}_{t+\Delta t} + (1 - \alpha) \dot{U}_t) + kU_{t+\Delta t} = F_t \quad (4.17)$$

- Typical Coefficient Values:

α : Governs numerical damping, typically ranging from -0.1 to -0.3 for seismic analysis. These coefficients follow the Newmark-Beta scheme:

$$\gamma = 0.5(1 - 2\alpha)$$

$$\beta = \frac{(1 - 2\alpha)^2}{4}$$

- Applications:

Widely used for dynamic analysis where numerical damping is needed for high-frequency modes.

Chung-Hulbert Method

- The Chung-Hulbert method enhances energy dissipation through controlled numerical damping.

- Equation:

$$M\ddot{U}_{t+\Delta t} + C(\alpha_m \dot{U}_{t+\Delta t} + (1 - \alpha_m) \dot{U}_t) + kU_{t+\Delta t} = F_t \quad (4.18)$$

- α_m : Governs numerical energy dissipation, typically ranging from 0.05 to 0.2.
- Additional coefficients for damping and stiffness are calibrated based on specific structural requirements.

- Applications:
Highly effective for suppressing spurious oscillations.
Commonly used in systems with high energy dissipation requirements, such as retrofitted structures.

Table 4.1. Comparison of Methods.

Method	Stability	Key Coefficients	Applications
Newmark-Beta	Unconditionally stable	β, γ	General-purpose dynamic analysis
Wilson-Theta	Unconditionally stable	θ	High stiffness systems
Collocation	Conditionally stable	Collocation weights	High-precision seismic modeling
Hilber-Hughes-Taylor	Unconditionally stable	α, γ, β	High-frequency oscillation control
Chung-Hulbert	Unconditionally stable	αm	Energy dissipation for highly nonlinear systems

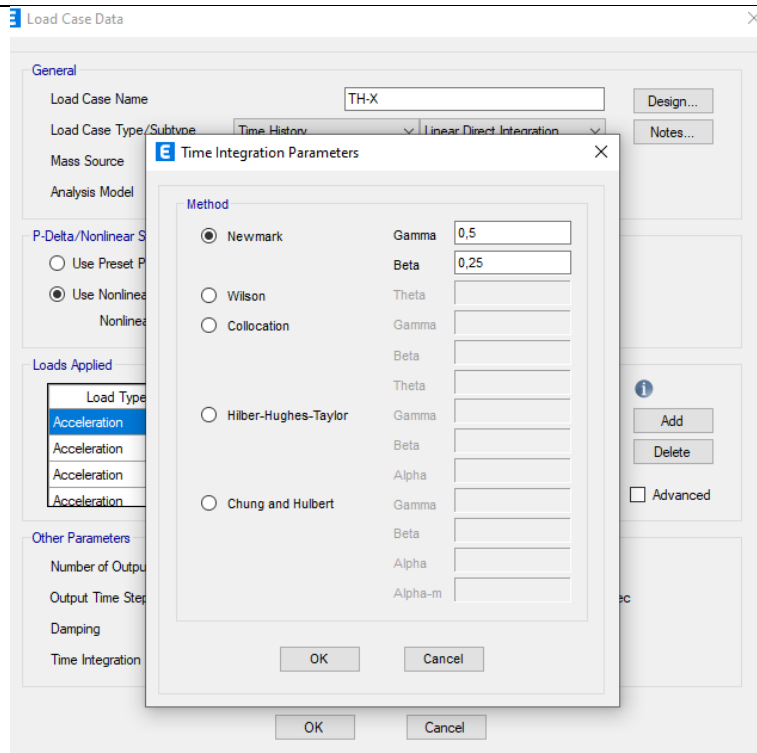


Fig 4.20. Time Integration Parameters and Method Selection in ETABS for Nonlinear Dynamic Analysis.

D. Structural Response Interpretation

∞ **Time-Dependent Response Metrics**

- **Displacement-Time Histories:** Captures the evolution of displacements at critical points (e.g., roof).
- **Interstory Drift Histories:** Evaluate relative displacements between floors.

∞ **Hysteretic Behavior**

Hysteresis loops for structural components highlight:

- **Energy Dissipation:** Represented by the enclosed area of the loop.
- **Stiffness Degradation:** Evident from shrinking loop sizes in cyclic loading.

∞ **Performance Assessment**

Performance levels are categorized as:

- **Immediate Occupancy (IO):** Minimal structural damage.
- **Life Safety (LS):** Significant damage but no collapse.
- **Collapse Prevention (CP):** Extensive damage nearing structural failure.

4.2.5 Seismic Resistance of Reinforced Concrete Structures

4.2.5.1 Required Seismic Resistance

Required seismic resistance refers to the minimum level of strength and stability necessary for a structure to withstand anticipated seismic forces. For RC structures in Algeria, this is determined using the seismic base shear force as per RPA 99/2003:

$$V = \frac{ADQ}{R} W \quad (4.19)$$

V: seismic base shear force,

A: zone acceleration coefficient (dependent on seismic zone),

D: mean dynamic amplification factor,

Q: Quality factor for materials and structural systems,

R: Structural behavior coefficient, reflecting ductility and redundancy,

W: Total weight of the structure.

4.2.5.2 Available and Residual Seismic Resistance

The seismic resistance of a structure can be categorized into available and residual capacities:

∞ **Available Seismic Resistance (V_c):**

- ✚ Represents the structure's base shear capacity before any seismic damage.
- ✚ Determined by the strength of vertical elements (columns and walls) in the elastic phase.
- ✚ Influenced by material quality (concrete strength, steel grade) and reinforcement detailing.

∞ **Residual Seismic Resistance (V_d):**

- ✚ Reflects the structure's remaining capacity post-earthquake, accounting for damage.

- ✚ Calculated by considering stiffness degradation in damaged elements.

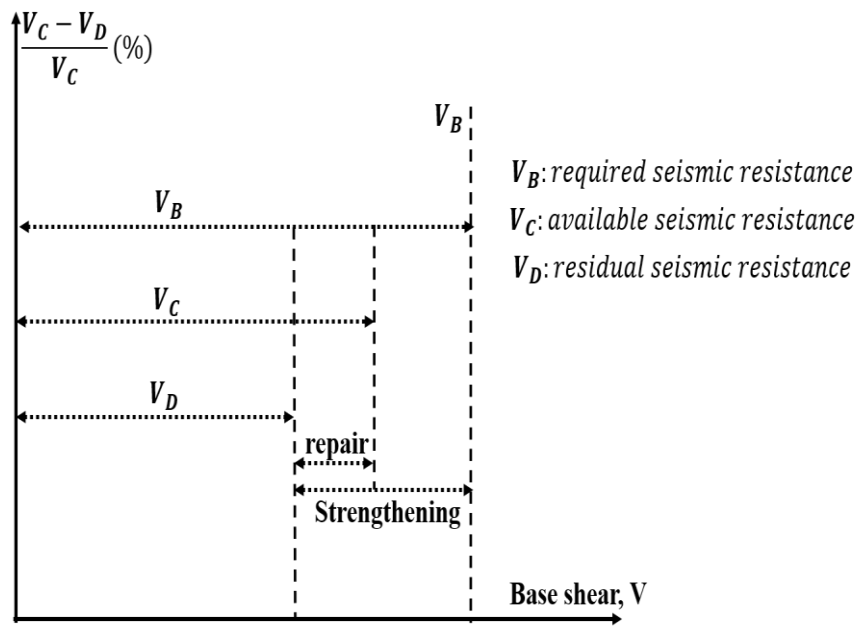


Fig. 4.21. Schematic representation of resistances V_B , V_C , and V_D [59].

∞ **Seismic loss (Δ_P):**

Seismic loss of resistance is defined as the difference between the available and residual seismic forces: $\Delta_P = V_C - V_D$ (4.20)

Residual resistance directly influences the level of rehabilitation required, ranging from basic repairs to structural strengthening.

4.2.5.3 Resistance Indices

Resistance indices are critical for evaluating seismic performance and planning rehabilitation:

∞ **Capacity Index R_C :**

$$R_C = \frac{V_C}{V_B} \tag{4.21}$$

Represents the ratio of available capacity to the initial base shear strength.

∞ **Damage Index R_D :**

$$R_D = \frac{V_D}{V_C} \tag{4.22}$$

Represents the ratio of residual capacity to available capacity, providing a measure of post-seismic functionality.

Practical Implications:

- ✚ Higher R_C and R_D values indicate better resilience.
- ✚ Rehabilitation strategies aim to restore R_D to acceptable levels, often aligning with RPA99/2003 criteria.

4.2.6 Ductility and Seismic Performance of Reinforced Concrete Structures

The seismic performance of reinforced concrete (RC) structures relies on two fundamental properties: strength and ductility. While strength ensures the structure can withstand applied loads, ductility enables it to sustain deformations beyond the elastic limit without sudden failure, dissipating seismic energy effectively. This section explores the concept of ductility at both the material and structural levels, its quantification, influencing factors, and its role in seismic performance.

4.2.6.1 Introduction to Ductility in Seismic Performance

Ductility refers to a structure's ability to undergo large inelastic deformations without significant loss of load-carrying capacity. In seismic events, ductility becomes crucial, allowing the structure to absorb and dissipate energy through plastic deformations, delaying collapse. A structure with adequate ductility can meet seismic design objectives, such as:

✚ **Life Safety:** Protecting occupants by preventing collapse.

✚ **Energy Dissipation:** Reducing seismic forces through inelastic deformations.

✚ **Controlled Damage:** Allowing repairable, localized failures without sudden collapse.

Seismic codes, including RPA 99/2003, emphasize designing ductile structures to ensure resilience under extreme ground motions.

4.2.6.2 Types of Ductility

Ductility can be classified into kinematic ductility and global ductility, depending on the scale of evaluation:

A. Kinematic Ductility

Kinematic ductility describes the deformation capacity at the material or structural element level.

∞ Material-Level Ductility (Strain-Based):

For materials, ductility is defined as the ratio of maximum strain (ε_{max}) to elastic strain (ε_y):

$$\mu = \frac{\varepsilon_{max}}{\varepsilon_y} \quad (4.23)$$

Where:

ε_{max} : Maximum strain before failure.

ε_y : Elastic yield strain.

∞ Element-Level Ductility (Displacement-Based):

For structural elements under axial load (tension/compression), kinematic ductility is expressed as:

$$\mu = \frac{\delta_{max}}{\delta_y} \quad (4.24)$$

Where:

δ_{max} : Maximum elongation/shortening.

δ_y : Elastic limit elongation/shortening.

For flexural elements under rotation:

$$\mu = \frac{\theta_{max}}{\theta_y} \quad (4.25)$$

Where:

θ_{max} : Maximum rotation.

θ_y : Elastic rotation limit.

B. Global Ductility

Global ductility characterizes the entire structure's behavior during seismic events. It is defined using displacement ductility:

$$\mu_d = \frac{\Delta_{max}}{\Delta_y} \quad (4.26)$$

Where:

Δ_{max} : Maximum displacement at collapse.

Δ_y : Displacement at the yield point.

Global ductility is crucial in pushover analysis and nonlinear dynamic simulations for evaluating seismic resilience.

4.2.6.3 Role of Ductility in Seismic Energy Dissipation

Ductility allows RC structures to dissipate seismic energy through inelastic deformations. The area under the force-displacement curve (hysteresis loops) represents the energy absorbed and dissipated by the structure during cyclic loading:

$$E_d = \int F d\Delta \quad (4.27)$$

Where:

E_d : Energy dissipated per cycle.

F : Lateral force.

Δ : Displacement.

4.2.6.4 Factors Influencing Ductility

Ductility depends on material behavior, reinforcement detailing, and structural design:

∞ Material Properties:

Concrete: Brittle behavior limits ductility, but confinement improves strain capacity.

Steel: High-yield strength and strain hardening enhance ductility.

∞ Reinforcement Detailing:

Confinement reinforcement (stirrups, ties) increases ductility by preventing concrete spalling.

Proper anchorage and lap splice ensure efficient force transfer.

∞ **Structural Configuration:**

Regular structures with well-detailed plastic hinges perform better under seismic loads.

∞ **Rehabilitation Techniques:**

FRP Jacketing: Enhances confinement, improving flexural ductility.

Shape Memory Alloys (SMAs): Provide superelastic behavior for energy dissipation.

4.2.6.5 Numerical Evaluation of Ductility

Using ETABS or similar software, ductility can be assessed through:

∞ **Nonlinear Static Analysis (Pushover Analysis):**

Identifies plastic hinge formation and evaluates global displacement ductility (μ_d).

∞ **Nonlinear Time-History Analysis:**

Simulates structural response to ground motion records, capturing inelastic deformations.

4.3. Conclusion

Chapter 4 presented a comprehensive investigation into the seismic behavior of reinforced concrete structures using advanced numerical modeling techniques. Through the application of ETABS software, the chapter examined critical parameters such as ductility, damping mechanisms, and nonlinear structural behavior, underscoring their pivotal roles in evaluating and enhancing seismic performance. These detailed analyses not only quantified the dynamic responses of RC structures under seismic loads but also offered a systematic approach to identifying vulnerabilities and optimizing structural resilience. By integrating the principles of the Algeria-specific seismic assessment framework established in Chapter 3, this chapter successfully combined theoretical foundations with cutting-edge numerical tools to create a holistic seismic performance evaluation and improvement methodology.

Looking ahead, Chapter 5 will focus on validating the proposed framework and methodologies through a series of case studies and real-world simulations. This research phase will rigorously test the reliability and applicability of the approaches outlined in Chapter 4, ensuring their effectiveness in practical scenarios. By bridging the gap between theoretical analysis and real-world implementation, Chapter 5 aims to solidify the practical contributions of this research to the seismic resilience of reinforced concrete structures.

Chapter 5: Case Studies and Framework Validation

*“Theory finds its
truth not in perfection, but in the structures that stand after the storm”*

5.1 Introduction

In the previous chapters, a comprehensive Algeria-specific seismic assessment framework was developed alongside advanced seismic evaluation techniques for reinforced concrete (RC) structures. This chapter aims to validate the framework's effectiveness by applying it to real-world and hypothetical case studies of RC structures, assessing their seismic resilience both before and after rehabilitation. The reliability of any seismic assessment framework depends on its ability to accurately reflect the performance of structures under seismic loads and its applicability in real-world scenarios. Therefore, it is essential to not only propose theoretical models but also to validate these models through practical, empirical data. This chapter serves as a critical step in ensuring that the framework developed in Chapter 3 can be successfully implemented in the Algerian context, where unique seismic, environmental, and resource constraints exist.

To achieve this, three key real-world case studies and one hypothetical case are used to evaluate the framework's applicability and effectiveness:

- The Pavilion of Urology at CHU Mustapha Pacha, a healthcare facility in Algiers, represents critical infrastructure subject to seismic risk.
- A Residential Building in Ibn Khaldoun Housing Estate (1200 Housing Units), a complex directly impacted by the devastating Zemmouri earthquake of 2003, represents a typical urban housing scenario in Algeria.
- Additionally, a hypothetical case is introduced, representing a generic RC structure typical in Algeria, allowing us to explore the framework's broader applicability to various building types.

These case studies aim to test the framework and evaluate the effectiveness of advanced rehabilitation techniques such as fiber-reinforced polymers (FRP), shape-memory alloys (SMAs), and energy dissipation devices in improving the seismic performance of these structures. This chapter aims to validate the proposed framework through detailed analysis and performance-based evaluation by assessing its impact on structural resilience, durability, and compliance with Algeria's seismic code, RPA 99/2003.

Ultimately, this chapter will provide empirical evidence supporting the integration of modern seismic assessment and rehabilitation techniques within the Algerian context, laying the foundation for enhanced resilience in existing and future infrastructure.

5.2 Validation Process

The validation process aims to rigorously test the proposed framework and rehabilitation techniques as outlined in *Chapter 3 and 2*. This phase focuses on confirming the seismic performance and structural resilience of rehabilitated RC structures under real-world conditions. Key aspects include:

- Evaluating how well the framework performs in predicting the seismic capacity of RC structures under different conditions and comparing its results with established seismic codes (e.g., RPA 99/2003).
- Testing the effectiveness of advanced techniques (such as fiber-reinforced polymers (FRP), shape-memory alloys (SMAs), and energy dissipation devices) in enhancing the seismic performance and durability of structures, as applied to the case studies.
- Ensuring that the proposed framework and rehabilitation techniques are adaptable to Algeria's local geotechnical, climatic, and resource conditions and are feasible regarding cost and availability.

“For further details on the validation criteria and methodology, please refer to Section 3.4 (“Framework Components”) and Section 3.5 (“Comparative Analysis with International Standards”) in Chapter 3, as well as Chapter 2 for the foundational rehabilitation techniques and Chapter 4 for numerical modeling and advanced assessment methods”.

5.2.1. Limitations and Assumptions

The validation process will rely on a set of assumptions and may face certain limitations:

- **Data Availability:** The accuracy of the validation results will depend on the quality and availability of detailed structural data and seismic hazard data.
- **Model Assumptions:** Some assumptions about material properties, boundary conditions, and loading scenarios will be made during numerical modeling. While these will be based on conservative values, they introduce inherent uncertainties into the results.
- **Specific Building Types:** While the selected case studies represent a range of typical structures in Algeria, the framework’s applicability to other building types may require further testing.

This validation process is designed to rigorously assess the effectiveness and practical applicability of the Algeria-specific seismic assessment framework and the advanced rehabilitation techniques. By evaluating how well the retrofitting techniques improve the seismic capacity and resilience of RC structures, this methodology ensures that the proposed

solutions are technically sound and capable of enhancing the seismic safety of Algeria's built environment.

5.3 Selected Case Studies

5.3.1 Criteria for Case Study Selection

The selection of case studies is a critical step in validating the proposed Algeria-specific seismic assessment framework and the rehabilitation techniques discussed in this thesis. To ensure that the case studies provide a diverse and representative sample, the following criteria were considered:

A. Location in High-Risk Seismic Zones in Algeria

The selected case studies are located in areas that are vulnerable to seismic activity, particularly in regions with a history of seismic events. Algeria's seismic zones, as defined by its national seismic code RPA 99/2003, range from low to high seismicity. Focusing on structures within high-risk seismic zones ensures that the case studies provide relevant data for the framework's application in areas with the most significant seismic vulnerability.

B. Variety in Structural Types

The case studies represent different types of reinforced concrete (RC) structures commonly found in Algeria, including residential buildings, public infrastructure, and commercial or administrative buildings. This diversity allows for a comprehensive evaluation of the framework's applicability across various structural typologies and their respective seismic performance needs. Each structural type presents unique challenges in terms of retrofitting and rehabilitation, making them suitable for testing the advanced rehabilitation techniques developed in the thesis.

C. Extent of Damage and Rehabilitation Requirements

The selected case studies include buildings with varying levels of seismic damage and rehabilitation history. Some structures have been affected by past seismic events, while others require retrofitting to improve their resilience. This variation provides an opportunity to test the framework's ability to assess post-seismic rehabilitation and evaluate the effectiveness of retrofitting techniques in improving seismic performance.

Combining these criteria ensures that the case studies comprehensively represent typical RC structures in Algeria and provide a robust testing ground for the proposed seismic assessment and rehabilitation framework.

5.3.2 Overview of Selected Structures

This section provides an in-depth overview of the three selected case studies, including detailed descriptions of the structures, their seismic vulnerabilities, and rehabilitation history. The

following case studies have been chosen to represent various structural types and damage levels, allowing for a thorough validation of the framework's effectiveness.

5.2.2.1 Case Study 1: Urology Pavilion, CHU Mustapha Pacha

Step 01: Data Collection

A. General Building Information

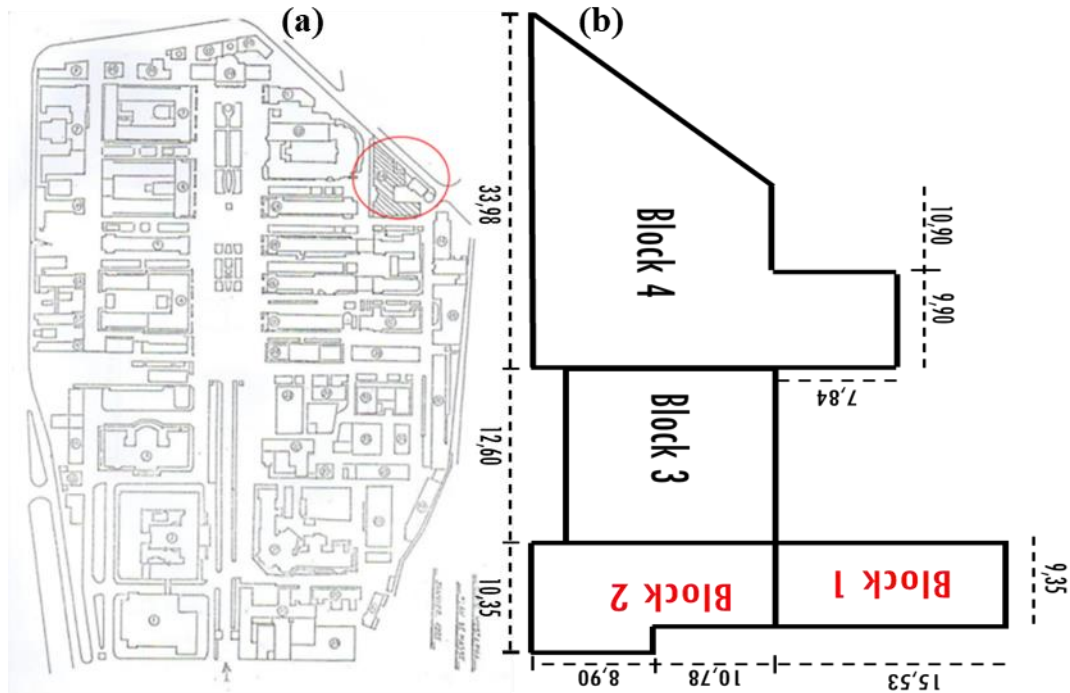


Fig 5.1. a) Layout Plan and b) Floor Plan of the Urology Pavilion, CHU Mustapha Pacha.
Table 5.1. Summary of General Information for the CHU Mustapha Pacha Pavilion of Urology.

Category	Details	
1. Location and Seismic Zone	Geographic Location	- Located in the municipality of Sidi M'Hamed, Algiers, Algeria. - One of the largest hospitals in Algeria, serving as a critical healthcare facility in the capital.
	Seismic Zone	- Algiers is classified under Seismic Zone III by RPA 99/2003, indicating a high seismic risk area.
2. Building Function	Purpose	- Pavilion of Urology: A specialized healthcare facility focused on urology-related medical care, diagnostics, and surgical interventions.
	Importance	- Serves over 10,000 outpatient consultations and 1,500+ inpatient treatments annually. - Plays an educational role in providing pre-graduate and post-graduate medical training.
3. Construction Era and Practices	Year of Construction	- Initially constructed in the 1940s during the colonial era.
	Design Standards Applied	- Pre-RPA 99/2003 seismic codes; no adequate seismic design provisions were included during initial construction and later modifications.
4. Structural Layout	Dimensions	- Overall plan dimensions: 56.93m × 35.21m. - Total height: 15.5m (ground floor + three stories).
	Load-Bearing Elements	- Combination of reinforced concrete moment frames and masonry infill.

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- Blocks 1 and 2 exhibit the most significant structural damage and seismic vulnerabilities.
- Key issues include visible cracking and concrete spalling in critical components (beams and columns).
- Structural deterioration caused by age, extensive modifications, and environmental exposure.



Fig 5.2. Exterior View of the Urology Pavilion, (a) Block I (b) Block II.

A. Structural Data Collection

Table 5.2. Detailed Structural and Site Data for Blocks I and II of CHU Mustapha Pacha.

Category		Details
1. Building Geometry and Layout	Block I	Dimensions: 9.35 m × 15.53 m. Structural system: Two (02) longitudinal and five (05) transverse RC frames.
	Block II	Dimensions: 9.35 m × 19.93 m. Structural system: Three (03) longitudinal and six (06) transverse RC frames.
2. Plates/Floors	Block I/Block II	Hollow-core concrete slabs, 20 cm thick.
3. Column Types	Block I	Exterior Columns (Edge Columns): 40 x 35 cm. Interior Columns (Central Columns): 30 x 35 cm.
	Block II	Exterior Columns (Edge Columns): 40 x 35 cm. Interior Columns (Central Columns): 30 x 40 cm (Middle sections), 30 x 35 cm (Some edge positions).
4. Beam Dimensions	Block I/ Block II	Transverse beams: 30 × 80 cm and 30 × 40 cm. Longitudinal beams: 35 × 40 cm.
5. Material Properties:	Block I/ Block II	Concrete
Steel Reinforcement		Based on NDT results (ultrasonic pulse velocity and Schmidt hammer tests) (See Table 5.3 for detailed properties) (See Table 5.4 for detailed steel reinforcement properties)
6. Reinforcement Detailing for Columns and Beams	Block I/ Block II	(See Table 5.5 for reinforcement details for columns and beams)
7. Beam-Column Joint Connections.	Block I/ Block II	See Table 5.6
8. Site-Specific Data Collection	Block I/ Block II	Soil Properties (See Table 5.7 for detailed soil properties)

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9. Seismic Hazard Data for the Site	Block I/ Block II	See Table 5.8
10. Historical Seismic Data	Block I/ Block II	(See Table 5.9 for detailed historical seismic data and impact on the structure)

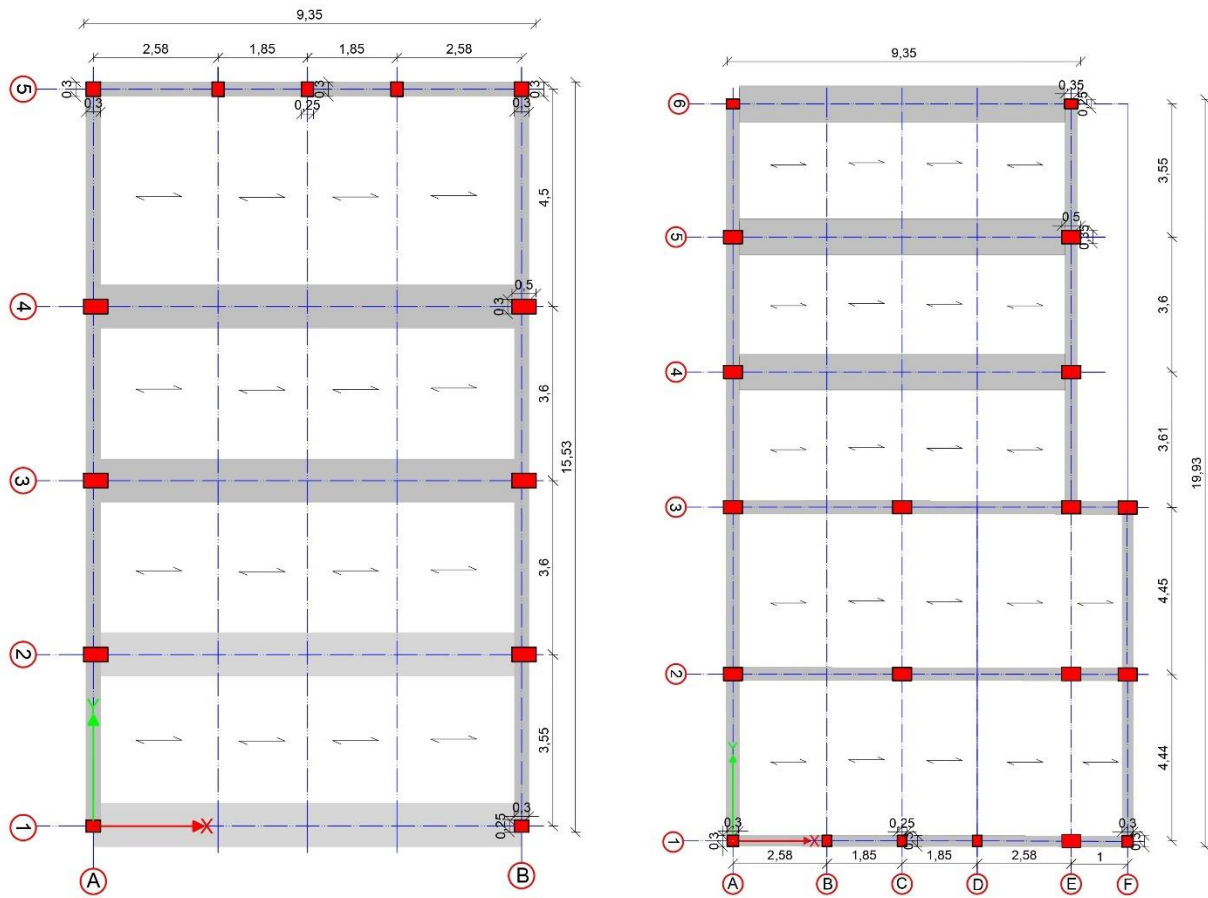


Fig 5.3. Plan View of Column Layout and Dimensions for Blocks I and II.

Table 5.3. Material Properties of Concrete for Blocks I and II.

Property	Block 1	Block 2
Compressive Strength (f_c)	16 MPa	18 MPa
Modulus of Elasticity (E)	18,800 MPa	19,900 MPa
Poisson's Ratio (ν)	0.2	0.2
Density (ρ)	2400 kg/m ³	2400 kg/m ³

Table 5.4. Steel Reinforcement Properties.

Property	Value
Reinforcement Grade	B300
Yield Strength (f_y)	300 MPa (B300)
Ultimate Tensile Strength	420 MPa

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Elastic Modulus (E)	200,000 MPa
Corrosion Level	Moderate to Severe

Table 5.5. Reinforcement Details for Columns and Beams in Blocks I and II.

Element	Level	Reinforcement Details
Columns (Block I)	Ground Floor	Longitudinal Bars: 4 Ø12mm Stirrups: Ø6 mm @ 300 mm spacing
	1st–3 rd Floors	Longitudinal Bars: 4 Ø10mm Stirrups: Ø6 mm @ 250 mm spacing
Columns (Block II)	Ground Floor	Longitudinal Bars: 4 Ø12mm Stirrups: Ø6 mm @ 300 mm spacing
	1st–3 rd Floors	Longitudinal Bars: 4 Ø10 mm Stirrups: Ø6 mm @ 250 mm spacing
Beams (Block I)	All Levels	Top/Bottom Reinforcement: 2 Ø10–Ø12 mm Stirrups: Ø6 mm @ 200 mm spacing
Beams (Block II)	All Levels	Top/Bottom Reinforcement: 2–3 Ø10–Ø12 mm Stirrups: Ø6 mm @ 250–300 mm spacing

Table 5.6. Observations on Beam-Column Joint Connections.

Aspect	Observation
Anchorage Length	Insufficient (short lap splices)
Bar Anchorage in Joints	Poor hook anchorage (90° hooks)
Confinement Reinforcement	Minimal stirrups at beam-column joints
Joint Integrity	Weak beam-column joints

Table 5.7. Soil Properties.

Property	Value/Details
Foundation Type	Shallow isolated footings
Soil Classification	S2 (Firm Soil)
Shear Wave Velocity (V_s)	(Assumed: 400-800 m/s)

Table 5.8. Seismic Hazard Data for the Site.

Property	Value/Details
Seismic Zone	Zone III (High Seismic Risk)
Peak Ground Acceleration (PGA)	0.40 g

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Table 5.9. Historical Seismic Data and Impact on the Structure.

Property	Details
Past Earthquakes	1980 El Asnam Earthquake (Magnitude 7.3)
	2003 Boumerdès Earthquake (Magnitude 6.8)
Impact on Structure	Existing structure not designed to modern seismic standards

B. Seismic Performance Evaluation

Table 5.10. Proposed Seismic Performance Levels (SPLs) for the Pavilion of Urology.

Performance Level	Objective	Indicators
Immediate Occupancy (IO)	The building should remain functional and safe immediately after an earthquake, serving critical healthcare functions.	- No structural damage to critical elements (e.g., beams, columns, shear walls). - Non-structural elements (partitions, windows) may have minor damage without impairing functionality.

Step 02: Structural Analysis Methods (Pre-Rehabilitation)

For the seismic performance evaluation of the Pavilion of Urology, pushover analysis was selected as the sole structural analysis method due to its practicality, focus on critical issues, and efficiency in guiding subsequent steps:

- Pushover analysis captures the structure's nonlinear behavior, which is essential for understanding its performance given its age, prior rehabilitation, and observed damage.
- It identifies failure modes (e.g., weak columns, beam-column joint deficiencies) and highlights critical vulnerabilities, providing insights into where and how the structure might fail during seismic events.
- Unlike linear static analysis, which assumes elastic behavior, pushover analysis reflects the actual inelastic performance of the building, making it more suitable for older, deteriorated structures.
- Nonlinear dynamic methods, such as time-history analysis, while more precise, are resource-intensive and rely on exact ground motion data, which may not add substantial value at this pre-rehabilitation stage.
- Pushover analysis generates a force-displacement curve, which allows one to evaluate a building's ability to meet Seismic Performance Levels (SPLs), such as Immediate Occupancy (IO).

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- It directly ties structural performance to specific objectives, aligning with modern performance-based seismic design principles.
- Pushover analysis provides all the necessary outputs (e.g., capacity vs. demand, failure mechanisms) to proceed seamlessly to:
 - Vulnerability assessment,
 - Capacity-demand comparison, and
 - Rehabilitation planning.

2.1. Results from Pushover Curves

2.1.1. Results for Block I

A. Capacity Curve:

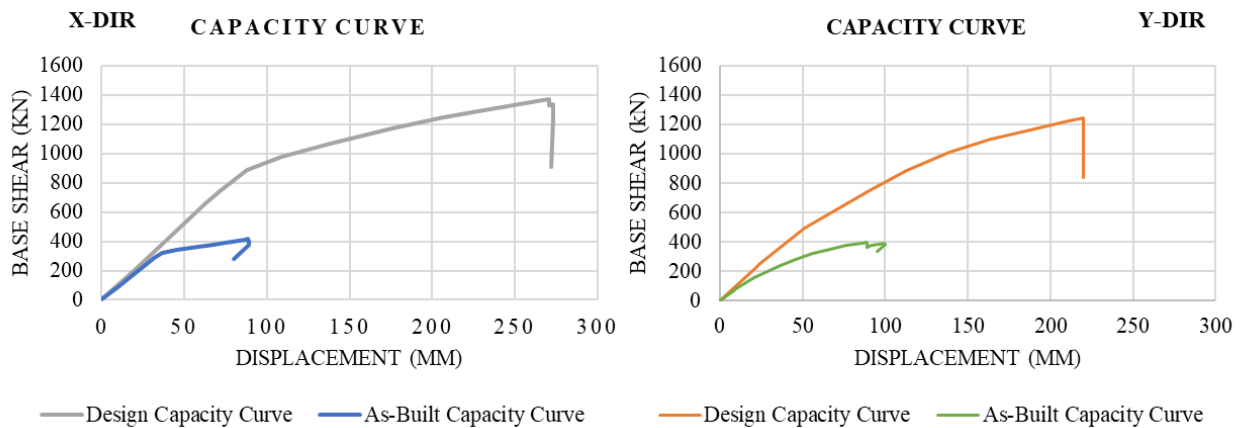


Fig 5.4. Capacity Curves for Block I: Actual vs. Design Performance in X and Y Directions.

B. Plastic Hinge Formation

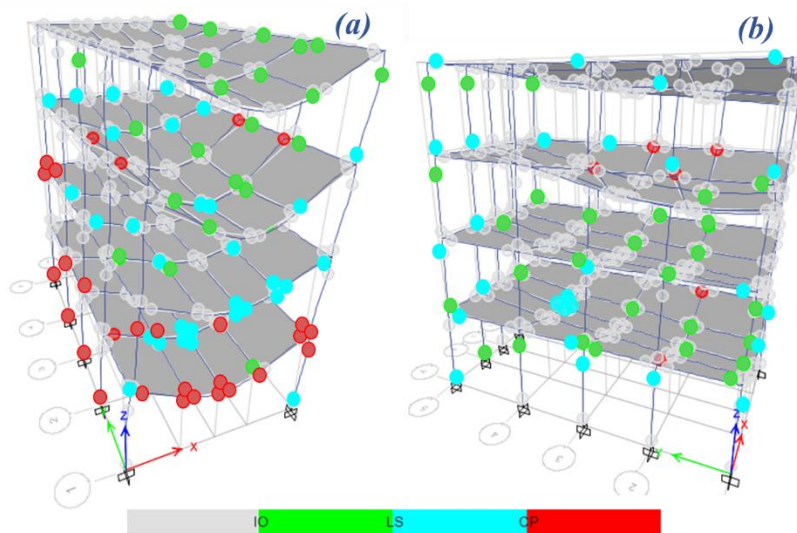


Fig 5.5. Plastic Hinge Distribution for Block I: X-Direction (a) vs. Y-Direction (b).

C. Inter-Story Drift Ratios

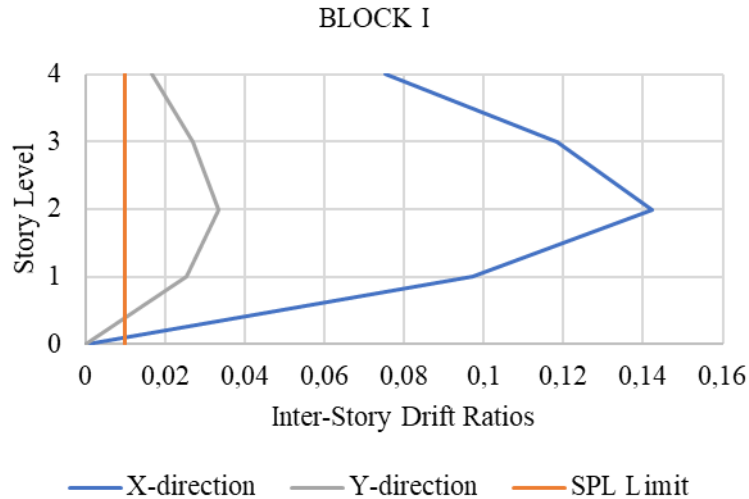


Fig 5.6. Inter-Story Drift Ratio Curves for Block I X and Y directions.

The capacity curve analysis for Block I highlights significant vulnerabilities in both the X and Y directions. In the X-direction, the actual capacity curve shows reduced stiffness, reflected in a shallower slope, indicating material deterioration and weak beam-column joints. The yield point occurs at approximately 250-300 kN (~50 mm displacement), which is lower than the design curve, showing premature yielding due to poor reinforcement and inadequate confinement. The peak base shear (~400 kN) is significantly lower than the design capacity (~1200 kN), and the sharp post-peak drop signals brittle failure mechanisms such as soft-story effects and joint failures. This is supported by the plastic hinge distribution, with a high concentration of collapse prevention (CP) hinges in the lower stories, indicating severe vulnerabilities. In the Y-direction, the capacity curve demonstrates better stiffness but still falls short of the design capacity. The yield point (~200-250 kN at ~40 mm displacement) occurs later than the X-direction, indicating relatively better performance. The peak base shear (~400 kN) is still lower than the design capacity (~1200 kN), but the post-peak behavior is smoother, suggesting ductile failure mechanisms and better seismic resilience.

The plastic hinge distribution confirms these results, with over 70% of CP hinges concentrated at the lower stories in the X-direction, reflecting a soft-story mechanism and brittle failure. In contrast, the Y-direction shows a more favorable distribution, with fewer CP hinges at the lower stories and more LS (life safety) and IO (immediate occupancy) hinges at mid-height and upper stories, indicating improved ductility and resilience.

The inter-story drift ratio analysis for Block I reveals severe vulnerabilities in the X-direction, with drift ratios exceeding allowable limits (up to 1.2% at the first floor), indicating soft-story effects. In contrast, the Y-direction performs better, with drift ratios remaining within acceptable limits (peaking at 0.4% at the third floor), reflecting improved stiffness and ductility. These

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findings emphasize the need for retrofitting in the X-direction to address brittle failure mechanisms, while preserving and enhancing the Y-direction's superior performance.

2.1.2. Results for Block II

A. Capacity Curve:

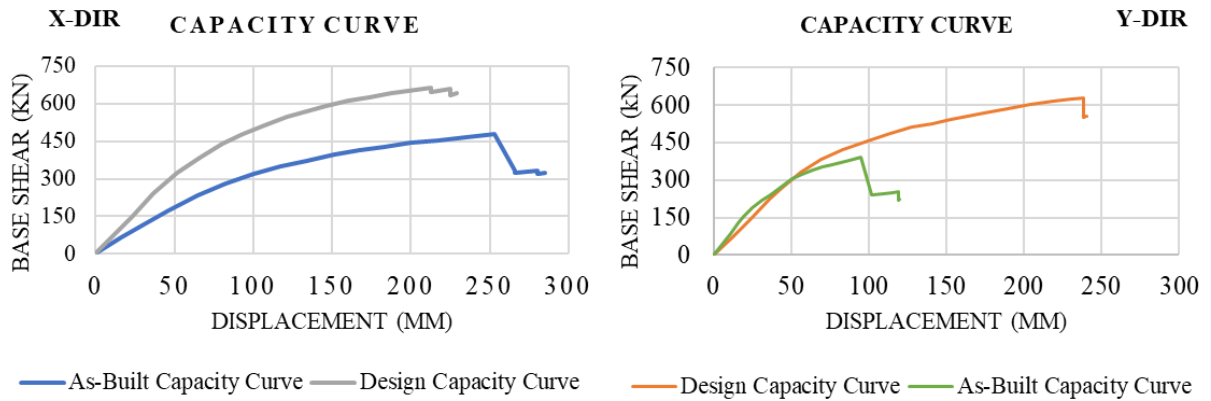


Fig 5.7. Capacity Curves for Block II: Actual vs. Design Performance in X and Y Directions.

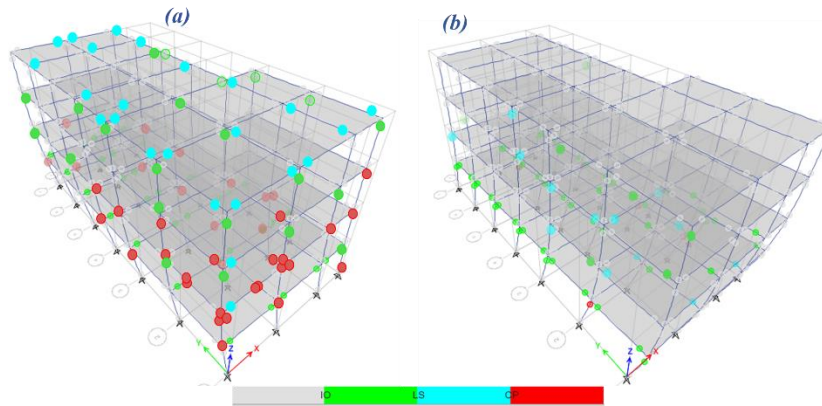


Fig 5.8. Plastic Hinge Distribution for Block II: X-Direction (a) vs. Y-Direction (b).

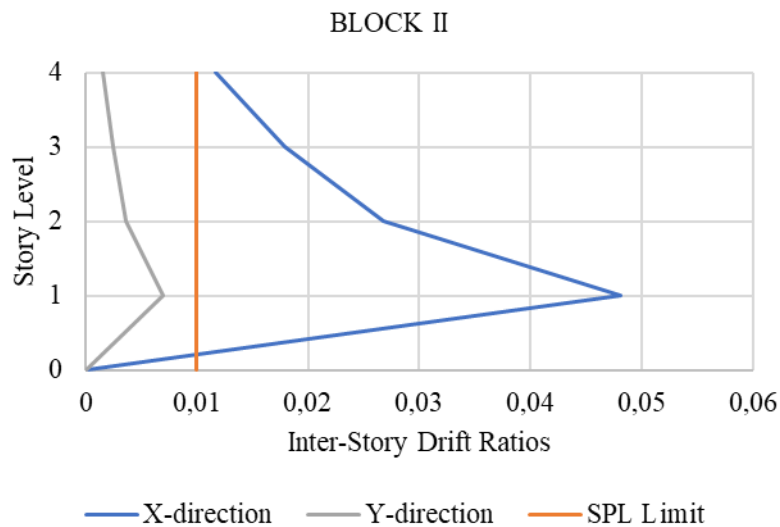


Fig 5.9. Inter-Story Drift Ratio Curves for Block II X and Y directions.

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The capacity curves for Block II in the X and Y directions highlight significant vulnerabilities compared to the design capacity curves. In the X-direction, the As-Built Capacity Curve exhibits a shallower slope, indicating reduced stiffness due to material degradation and poor detailing. The yield point occurs earlier (~300 kN at ~75 mm displacement) compared to the design curve, reflecting premature yielding caused by weak beam-column joints and inadequate reinforcement. The peak base shear (~450 kN) is substantially lower than the design capacity (~700 kN), with a sharp post-peak drop signaling brittle failure mechanisms such as soft-story behavior and joint failures, which represent critical vulnerabilities in this direction. In the Y-direction, the As-Built Capacity Curve shows better stiffness but still falls short of the design curve. The yield point (~350 kN at ~50 mm displacement) is delayed compared to the X-direction, reflecting better column alignment. However, the peak base shear (~500 kN) is still far below the design capacity (~700 kN), indicating significant strength loss. The post-peak behavior, though smoother than the X-direction, suggests brittle failure mechanisms, despite the Y-direction being more ductile and resilient than the X-direction. These findings underscore the need for targeted rehabilitation in the X-direction to address stiffness and ductility deficiencies and enhance the overall seismic performance of Block II.

The plastic hinge distribution for Block II reveals critical insights into the structural vulnerabilities in both directions. In the X-direction, a high concentration of collapse prevention (CP) hinges at the lower stories, particularly at column bases and beam-column joints, highlighting significant structural weaknesses such as soft-story mechanisms and brittle failure due to insufficient reinforcement. Hinges (LS) dominate the mid-height stories, indicating inelastic deformation before collapse, while hinges (IO) are limited to the upper stories, showing reduced ductility and stiffness. In contrast, the Y-direction exhibits a more favorable hinge distribution, with minimal CP hinges concentrated only at specific base joints, indicating reduced vulnerability. Hinges (LS) are primarily found in the mid-height, showing energy dissipation through ductile behavior, and hinges (IO) dominate the upper stories, reflecting the structure's ability to perform elastically under seismic loads.

The inter-story drift ratio analysis for Block II reveals the critical seismic vulnerabilities of both directions. In the X-direction, drift ratios exceed allowable limits at mid-height stories, indicating localized vulnerabilities and insufficient stiffness, as seen in the hinge concentration and limited ductility in the capacity curve. Meanwhile, the Y-direction performs better, with drift ratios mostly within the allowable range, reflecting improved stiffness, ductility, and overall seismic resilience. These results emphasize the urgent need for retrofitting in the X-

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direction to address soft-story effects and mid-height vulnerabilities, while leveraging the Y-direction's superior performance.

2.2. Vulnerability Assessment

The seismic vulnerability assessment of Blocks I and II was conducted based on a detailed analysis of their structural performance under seismic loading conditions. The evaluation integrates the results from the capacity curves, plastic hinge distributions, and inter-story drift ratios (ISDR), providing a comprehensive understanding of the blocks' deficiencies and resilience. This section synthesizes these findings to argue the structural vulnerabilities and identify critical areas requiring intervention.

Table 5.11. Vulnerability Assessment for Blocks I and II.

Aspect	Block I	Block II	Evidence/Results Supporting the Vulnerability
Stiffness Reduction	Severe reduction in X-direction, shallower slope in the capacity curve.	Moderate reduction in X-direction, slightly better than Block I.	Capacity curves show reduced stiffness; X-direction slopes are significantly flatter than design curves.
Premature Yielding	Early yielding at ~250-300 kN in the X-direction and ~200-250 kN in the Y-direction.	Yielding delayed in the Y-direction (~350 kN), but early yielding at ~300 kN in the X-direction.	Capacity curves demonstrate premature yielding, particularly in the X-direction, due to weak reinforcement and material degradation.
Soft-Story Behavior	Pronounced in the lower stories of the X-direction with excessive inter-story drift ratios.	No significant soft-story behavior was observed.	Inter-story drift ratios exceed allowable limits in the X-direction for Block I, indicating weak lower-story columns.
Mid-Height Vulnerabilities	Minor vulnerabilities at mid-height stories.	Significant vulnerabilities at mid-height in X-direction, with excessive drift ratios.	ISDR for Block II shows large drifts at mid-height in the X-direction, reflecting localized stiffness deficiencies.
Beam-Column Joint Weakness	Weak joints in both directions, early hinge formation, and CP hinges at joint locations.	There are weak joints in both directions; CP and LS hinges are concentrated at beam-column joints.	Plastic hinge distributions reveal joint failures with CP and LS hinges in critical areas, indicating shear deficiencies and insufficient transverse reinforcement.

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Brittle Failure	Significant brittle failure mechanisms, sharp post-peak drop in X-direction capacity curve.	Limited ductility in the X-direction with brittle failure mechanisms; moderate ductility in the Y-direction.	Capacity curves and hinge distribution highlight sharp post-peak drops, limited IO hinges, and poor energy dissipation in X-directions.
Base Shear Capacity	~400 kN in both X and Y directions, significantly below design capacity (~1200 kN).	~450 kN (X-direction) and ~500 kN (Y-direction), significantly below design capacity (~700 kN).	Capacity curves show actual base shear capacities are far below RPA 99/2003 requirements, highlighting seismic demand mismatch.
Ductility	Poor ductility in both directions; minimal IO hinges, particularly in the X-direction.	Moderate ductility in the Y-direction; poor in the X-direction, with limited IO hinges and high LS/CP hinge counts.	Plastic hinge distributions reveal fewer IO hinges and a higher proportion of LS and CP hinges in X-directions.
Collapse Risks	High collapse risk in the X-direction due to soft-story effects and brittle column failures.	Collapse risks in the X-direction are localized to mid-height stories; the Y-direction shows lower collapse risk.	The concentration of CP hinges in the X-direction for Block I (lower stories) and Block II (mid-height stories) indicates collapse-prone areas.

2.3. Seismic Capacity vs. Demand Comparison

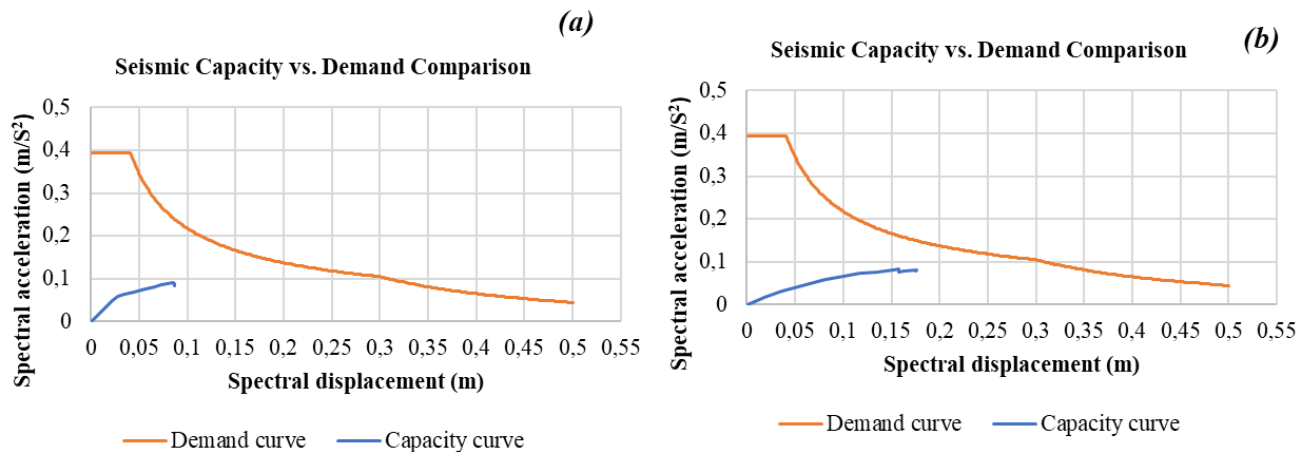


Fig 5.10. Seismic Capacity vs. Demand Comparison for Block I: X-Direction (a) vs. Y-Direction (b). The Capacity vs. Demand Comparison for Block I reveals significant seismic vulnerabilities in both the X- and Y-directions. In the X-direction, the capacity curve remains entirely below the demand curve, indicating a severe inability to meet seismic demands. The structure demonstrates premature yielding at approximately 0.05 m spectral displacement, reflecting low ductility, weak beam-column joints, and brittle failure mechanisms, which are critical

deficiencies. The capacity curve exhibits slightly better performance in the Y-direction with a more extended elastic range and higher stiffness. However, it still fails to intersect the demand curve, confirming that the structure is unable to sustain the required seismic demands. While the Y-direction shows improved ductility compared to the X-direction, localized weaknesses, such as insufficient lateral reinforcement and material degradation, significantly limit its capacity. These findings emphasize the need for immediate retrofitting, including strengthening beam-column joints, enhancing ductility with advanced materials, and mitigating seismic forces using energy dissipation devices to ensure structural resilience.

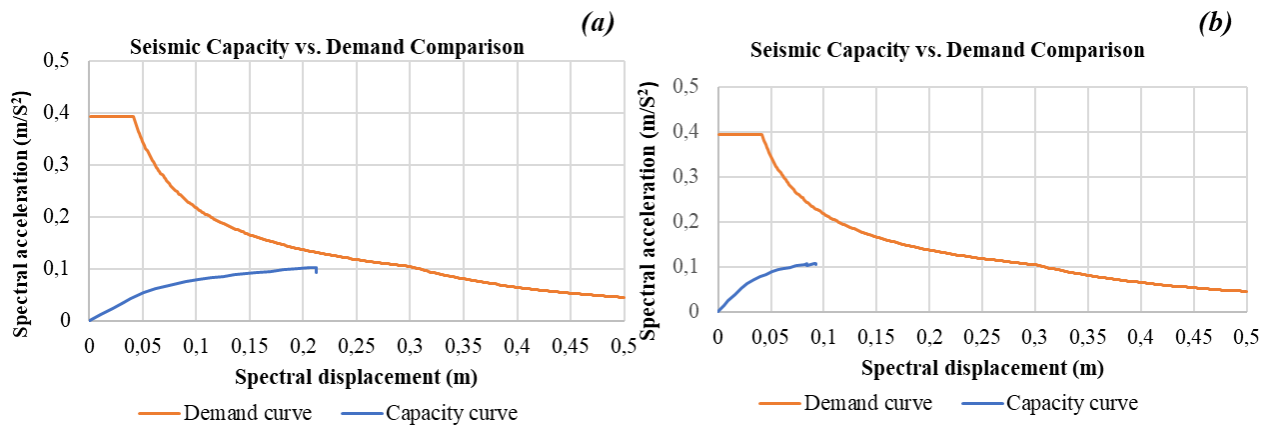


Fig 5.11. Seismic Capacity vs. Demand Comparison for Block II: X-Direction (a) vs. Y-Direction (b). The Capacity vs. Demand Comparison for Block II reveals critical seismic deficiencies in both directions. The capacity curve demonstrates insufficient stiffness in the X-direction, as indicated by the shallower slope observed in the pushover analysis. This reflects vulnerabilities such as weak beam-column joints and premature yielding, where structural weaknesses concentrate deformation at lower stories, significantly reducing seismic resilience. Additionally, the structure exhibits brittle failure mechanisms, as evident from its inability to sustain displacement or dissipate energy beyond elastic limits. Similarly, although the capacity curve demonstrates better stiffness and ductility in the Y-direction, it still fails to intersect the demand curve, highlighting localized vulnerabilities like plastic hinge concentration at mid-height stories and limited ability to resist seismic demands. These findings emphasize the urgent need for targeted retrofitting strategies to strengthen critical joints, improve ductility, and enhance the overall seismic capacity of Block II to meet Algeria's RPA 99/2003 requirements.

Step 03: Rehabilitation Strategy Design

Based on the findings from *Step 01: Data Collection and Step 02: Seismic Performance Evaluation*, it is evident that Blocks I and II exhibit significant seismic performance deficiencies. These include soft-story effects, weak beam-column joints, reduced stiffness, and limited ductility in both X- and Y-directions. The rehabilitation strategy in this step is designed

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to address these vulnerabilities by incorporating advanced materials, localized strengthening, and modern seismic mitigation techniques to enhance structural resilience and ensure compliance with Algeria's seismic code, RPA 99/2003.

3.1. Damage Classification

Table 5.12. Damage Classification for Blocks I and II.

Block	Direction	Damage Classification	Severity	Reason	Structural Elements Affected
Block I	X-Dir	Severe Damage	Critical	Inability to meet seismic demands, premature yielding, soft-story behavior	Beam-column joints, lower-story columns,
	Y-Dir	Moderate Damage	Moderate	Better stiffness and ductility, but localized damage at mid-height levels, and insufficient lateral reinforcement	Columns and joints at mid-height stories.
Block II	X-Dir	Severe Damage	Critical	Reduced stiffness, low ductility, mid-height vulnerabilities, early yielding, and joint failure	Beam-column joints and mid-height columns.
	Y-Dir	Moderate Damage	Moderate	Improved stiffness and ductility, but still fails to meet seismic demands and has localized damage	Mid-height columns and joints.

Conclusion

- ∞ Block I suffers from Severe Damage in the X-direction, primarily due to soft-story effects, while the Y-direction shows Moderate Damage with localized vulnerabilities.
- ∞ Block II experiences Severe Damage in the X-direction, with significant mid-height vulnerabilities and brittle behavior, while the Y-direction demonstrates Moderate Damage due to localized weaknesses.

3.2. Rehabilitation Technique for Block I Using the Hybrid SMA-FRP Reinforcement System

The use of advanced materials such as Fiber Reinforced Polymers (FRP) and Shape Memory Alloys (SMA) has revolutionized seismic retrofitting of reinforced concrete (RC) structures due to their superior performance in enhancing stiffness, strength, and ductility. Recent studies have highlighted the effectiveness of FRP in improving the load-bearing and energy-dissipation

capacities of RC elements. For instance, FRP wrapping has been shown to significantly enhance the ductility and confinement of RC columns, making them more resilient under seismic loads, as observed in a case study on low-ductility RC frame structures [60]. Similarly, SMA-based reinforcements provide exceptional post-yield deformation recovery and energy dissipation capabilities, as demonstrated in studies combining SMA and FRP in hybrid retrofitting systems for RC joints [61]. These systems are particularly effective in addressing brittle failures and joint vulnerabilities in RC structures, as shown in the use of externally applied SMA plates for minimally invasive retrofitting of beam-column joints [62], and the seismic assessment of RC bridge columns retrofitted with near-surface mounted SMA techniques [63].

Given the vulnerabilities identified in Block I, such as soft-story effects, joint weaknesses, and poor ductility, the Hybrid SMA-FRP Reinforcement System is a highly suitable solution. This approach directly addresses these deficiencies, ensuring improved seismic resilience and compliance with Algeria's seismic code RPA 99/2003.

3.2.1. Objectives of Rehabilitation

✚ X-Direction:

Mitigate soft-story effects by enhancing the stiffness and strength of lower-story columns;
Strengthen beam-column joints to reduce shear vulnerability and prevent brittle failures;
Improve overall ductility and ensure better energy dissipation to reduce collapse risks.

✚ Y-Direction:

Strengthen mid-height columns where plastic hinges are concentrated during seismic loading;
Improve the energy dissipation and post-yield deformation capacity of critical structural elements; Ensure sufficient capacity to meet seismic demands.

3.2.2. Modeling the Hybrid SMA-FRP Reinforcement System in ETABS

3.2.2.1. Material Properties for:

A. Shape Memory Alloy (SMA)

SMA braces, typically made from nickel-titanium (NiTi) alloys, possess super elasticity, shape memory effect, and excellent energy dissipation. Their mechanical properties are determined by composition and thermomechanical treatment. In this study, the mechanical properties used for SMA braces are derived from the Experimental Investigation of Mechanical Properties of NiTi Superelastic Shape Memory Alloy Cables by Lian et al. [64]. **Table 5.13** outlines critical properties, including transformation temperatures (A_s , A_f , M_s , M_f) and stress thresholds (σ_{A_s} , σ_{A_f} , σ_{M_s} , σ_{M_f}). **Fig. 5.14a** shows the phase transformation behavior, while **Fig. 5.14b** illustrates the stress-strain response, highlighting SMAs' super elasticity, which allows them to recover shape after significant strain.

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Table 5.13. summarizes the critical mechanical properties of the NiTi-based SMA material used in this study.

Property	Value	Property	Value
Austenitic Start Temperature (A_s)	-10 °C	Austenitic Strain at Start (ϵ_{As})	0.013125
Austenitic Finish Temperature (A_f)	18 °C	Austenitic Strain at Finish (ϵ_{Af})	0.09025
Martensitic Start Temperature (M_s)	14 °C	Martensitic Strain at Start (ϵ_{Ms})	0.078653
Martensitic Finish Temperature (M_f)	-16 °C	Martensitic Strain at Finish (ϵ_{Mf})	0.005156
Austenitic Start Stress (σ_{As})	195 MPa	Superelastic Plateau Strain Length (ϵ_L)	0.07
Austenitic Finish Stress (σ_{Af})	165 MPa	Maximum Residual Strain (ϵ_r)	6%
Martensitic Start Stress (σ_{Ms})	420 MPa	Young's Modulus (Austenite) (EA)	32000 MPa
Martensitic Finish Stress (σ_{Mf})	450 MPa	Young's Modulus (Martensite) (EM)	22222 MPa

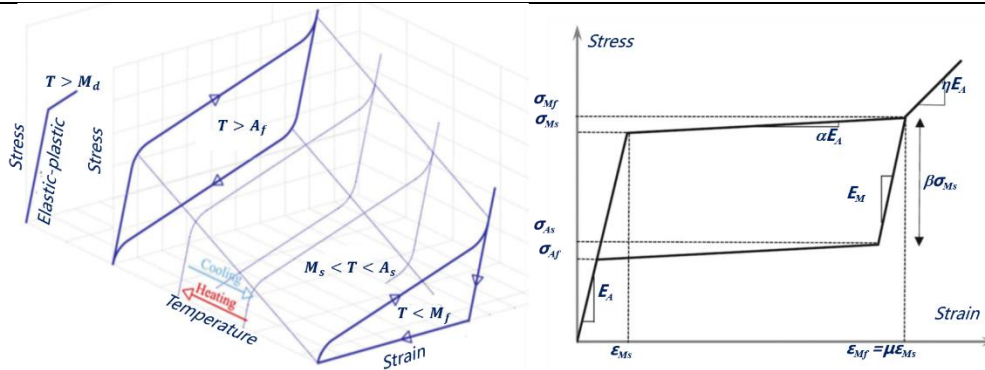


Fig. 5.12 a) Superelastic Behavior and b) Phase Transformation of SMA Modelling and identification of material

SMA brace hysteresis behavior was accurately modeled using multi-linear plastic and elastic link properties in ETABS. The plastic link (**Fig. 5.15a**) models the hysteresis loop, capturing energy dissipation, while the elastic link (**Fig. 5.15b**) models the flag-shaped force-deformation response. Parameters like unloading stiffness and residual strain (ϵ_r) were calibrated to represent the SMA brace behavior in seismic conditions accurately.

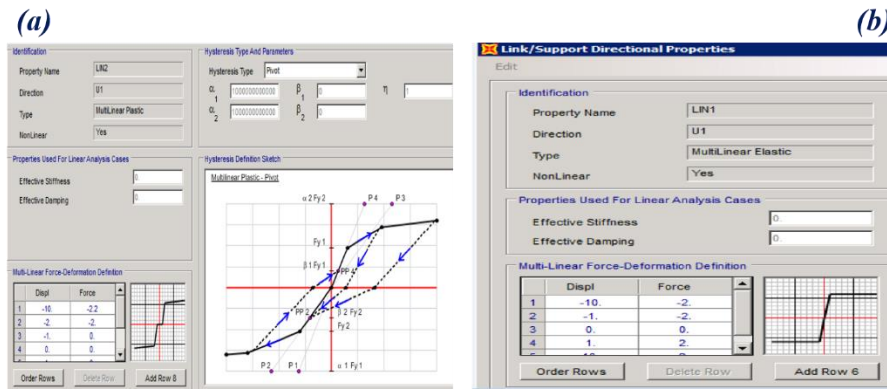


Fig. 5.13 a) Multi-linear Plastic link property using Pivot hysteresis, b) Multi-linear Elastic link property [55].

B. Fiber Reinforced Polymer (FRP)

Carbon Fiber Reinforced Polymer (CFRP) is chosen for the FRP component due to its superior performance in strengthening and retrofitting RC structures. CFRP provides exceptional tensile strength, stiffness, and durability, making it highly effective for mitigating seismic vulnerabilities in Block I. Several studies [65], [66] Validate the use of CFRP, including findings that show improvements in peak load capacity, ductility, and overall structural resilience.

In this study, we used the validated numerical and experimental properties of CFRP provided by the study by Dong et al [67]. These properties ensure accuracy in modeling and reflect the real-world performance of CFRP retrofitting.

Table 5.14. CFRP Properties.

Property	Value
Mass Density	1580 kg/m ³
Young's Modulus (Longitudinal)	138 GPa
Young's Modulus (Transverse)	9.65 GPa
Poisson's Ratio	0.021
Shear Modulus	5.24 GPa
Longitudinal Tensile Strength	2280 MPa
Transverse Tensile Strength	57 MPa
Shear Strength	71 MPa
Thickness (t)	0.68 mm (Corresponds to 4 layers, ensuring effective confinement and structural strengthening).

Modelling and identification of material

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CFRP was modeled in ETABS using layered shell elements to accurately represent its confinement and strengthening effects on reinforced concrete components. The layered shell approach simulates CFRP's orthotropic behavior, capturing its high stiffness and tensile strength in the longitudinal direction while accounting for moderate properties in the transverse direction. Key parameters such as thickness (0.68 mm per 4 layers) and bond strength were calibrated to reflect experimental data. The interaction between CFRP and concrete was modeled using adhesion properties, ensuring realistic load transfer and confinement effects during seismic loading. This approach effectively improves retrofitted elements' flexural, axial, and shear capacity.

3.2.2.2. Strategy for Applying SMA and CFRP

Table 5.15. Application Strategy for CFRP Wraps and SMA Brace.

Technique	Element	Application	Purpose	Justification
CFRP Wraps	Columns	Wrap all ground and first-floor columns circumferentially using a wet-layup process.	- Improve axial and flexural strength. - Enhance confinement to delay brittle failure.	- Provides passive reinforcement for critical load-bearing elements. - Minimizes disruption.
	Beams	- Apply CFRP wraps along the sides and bottom faces.	- Enhance shear and flexural capacities. - Prevent flexural cracking and buckling.	- Addresses shear deficiencies effectively. - Strengthens critical flexural zones.
	Beam-Column Joints	Use U-shaped CFRP wraps around joints for confinement.	Improve shear strength and joint integrity.	- Prevents brittle failures in joints. - Enhances durability under seismic forces.
SMA Braces		Install X-SMA braces in X-direction frames using bolted or welded connections.	Improve lateral stiffness. - Reduce inter-story drifts. - Provide energy dissipation during seismic events.	-SMA's superelastic properties ensure effective energy dissipation and self-centering. - Addresses soft-story effects.
General Notes		- Ensure CFRP overlaps of at least 150 mm for continuity. - Align and tension SMA braces precisely.		- Guarantees robust and effective retrofitting.

3.3. Seismic Analysis Methodology

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This section presents the seismic analyses performed to evaluate the retrofitted Block I of the Urology Pavilion at CHU Mustapha Pacha. The analyses include pushover and nonlinear time history analyses (NTHA) conducted in ETABS. After implementing the hybrid SMA-FRP retrofitting system, these methods provide insights into the structure’s static and dynamic seismic performance.

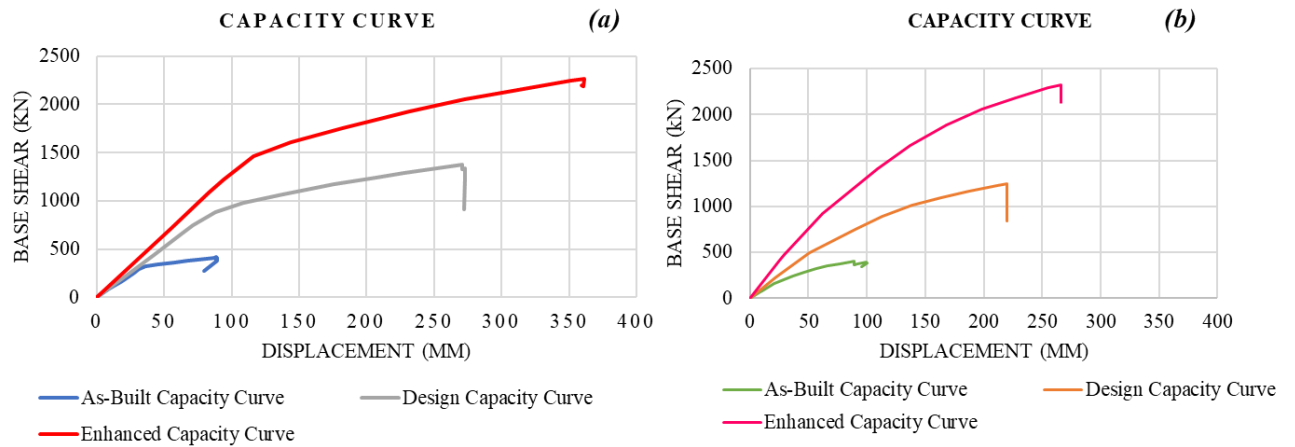
Table 5.16. Summary of Seismic Performance Evaluation Methods for Block I.

Analysis Method	Parameters & Details
Pushover Analysis	<p>Purpose: Evaluate seismic performance of Block I post-retrofitting.</p> <hr/> <p>Load Patterns:</p> <ul style="list-style-type: none"> - Uniform Load Pattern: Lateral forces distributed equally across floors. - Modal Load Pattern: Lateral forces based on structure’s fundamental vibration mode. <hr/> <p>Plastic Hinge Assignments:</p> <ul style="list-style-type: none"> - Columns: Axial-flexural hinges (P-M2-M3) to account for combined axial and bending effects. - Beams: Flexural hinges (M3) for bending failure. - SMA Braces: Axial-only hinges to model tension-compression behavior. <hr/> <p>Performance Levels Evaluated:</p> <ul style="list-style-type: none"> - Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP) thresholds as per FEMA 356 guidelines.
Nonlinear Time History Analysis	<p>Purpose: Evaluate dynamic performance under earthquake scenarios.</p> <hr/> <p>Ground Motion Records:</p> <ul style="list-style-type: none"> - El Asnam Earthquake (1980): PGA = 0.30 g - Boumerdès Earthquake (2003): PGA = 0.35 g - El Centro Earthquake (1940): PGA = 0.31 g <hr/> <p>Numerical Integration Technique:</p> <ul style="list-style-type: none"> - Newmark-Beta Method: Parameters: Beta = 0.25 (Constant Acceleration Method), Gamma = 0.5

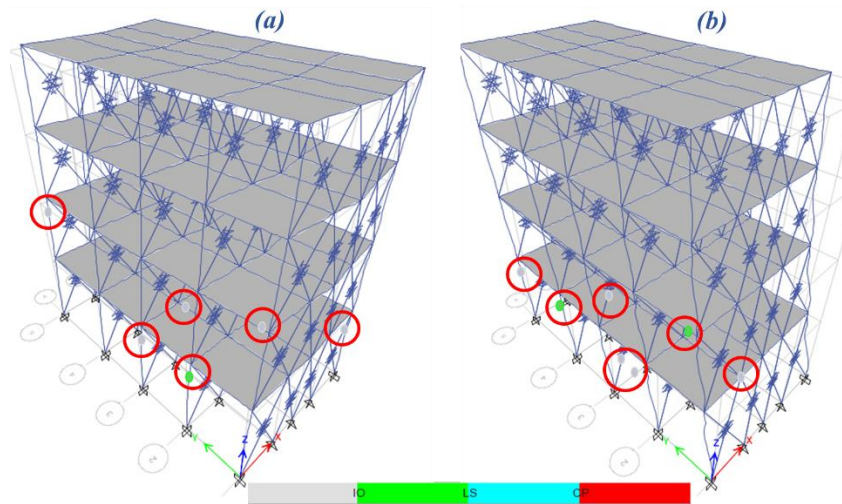
3.3.1. Seismic Performance Results and Evaluation of Retrofitted Block I

3.3.1.1. Pushover Analysis Results

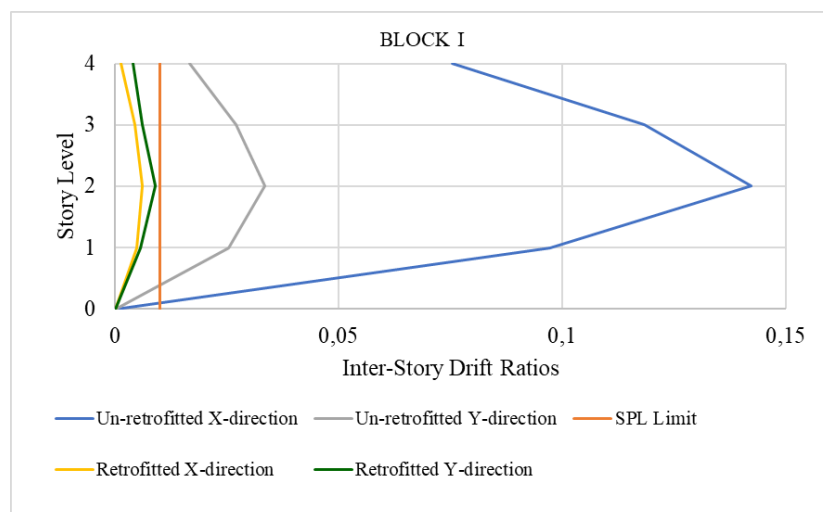
A. Capacity curve:



B. Plastic Hinge Formation



C. Inter-Story Drift Ratios



C. Seismic Capacity vs. Demand Comparison

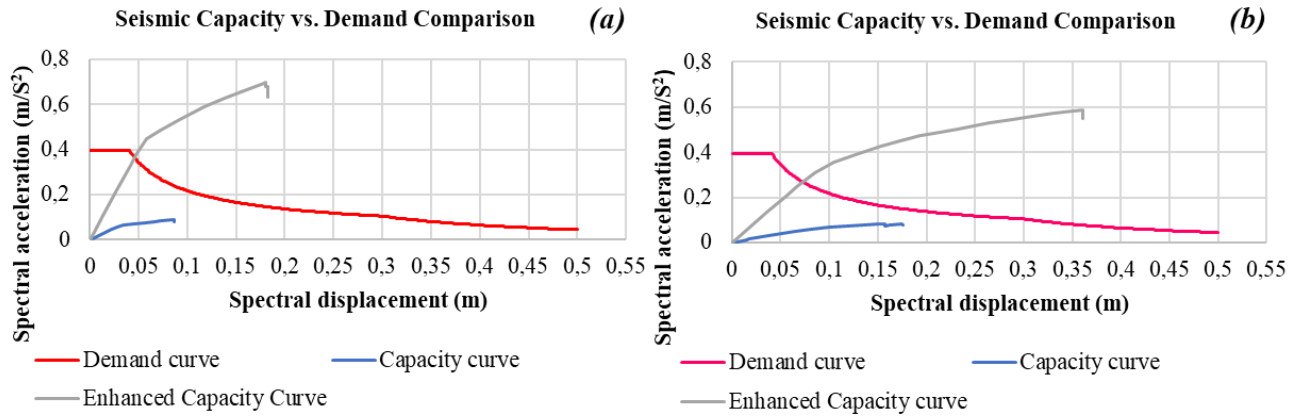


Fig. 5.17 Seismic Capacity and Enhanced Capacity vs. Demand Comparison for Block I: X-Direction (a) vs. Y-Direction (b).

3.3.2.1. Nonlinear Time History Analysis (NTHA) Results

A. Residual displacement

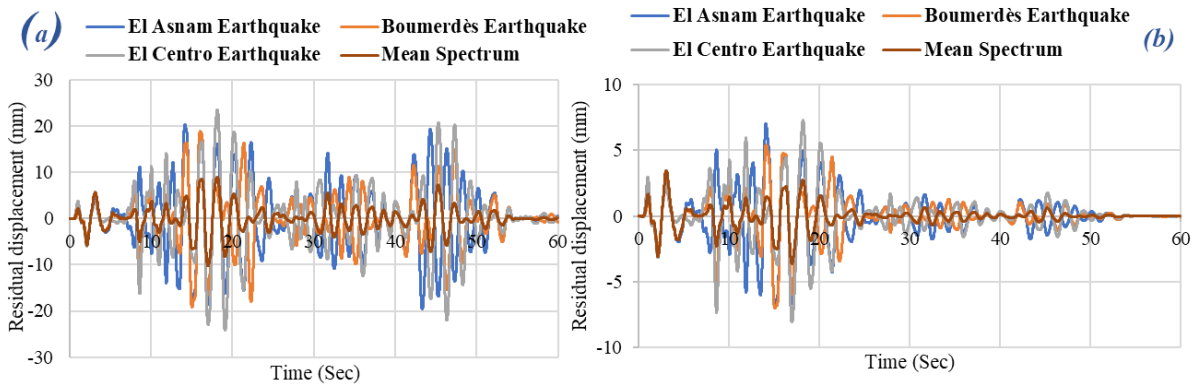


Fig. 5.18 Residual Displacement Time Histories for Block I in the X-Direction: (a) Un-Retrofitted vs. (b) Retrofitted.

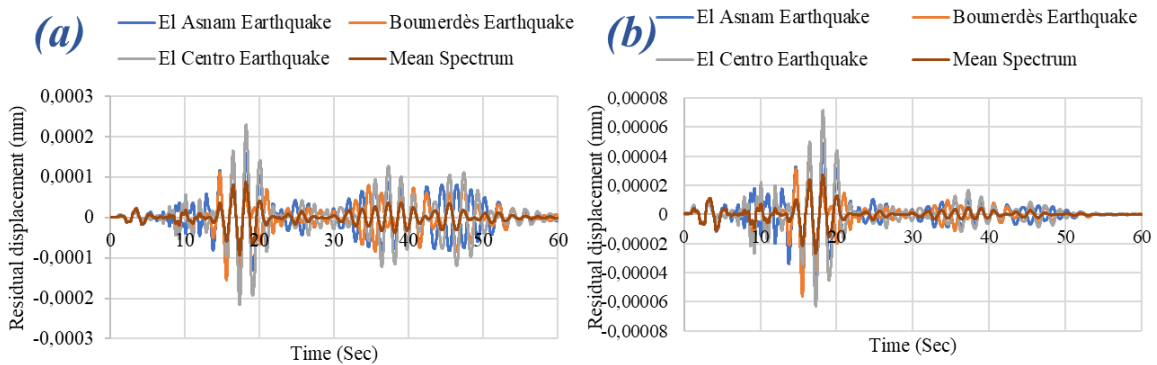


Fig. 5.19 Residual Displacement Time Histories for Block I in the Y-Direction: (a) Un-Retrofitted vs. (b) Retrofitted.

B. Peak floor acceleration

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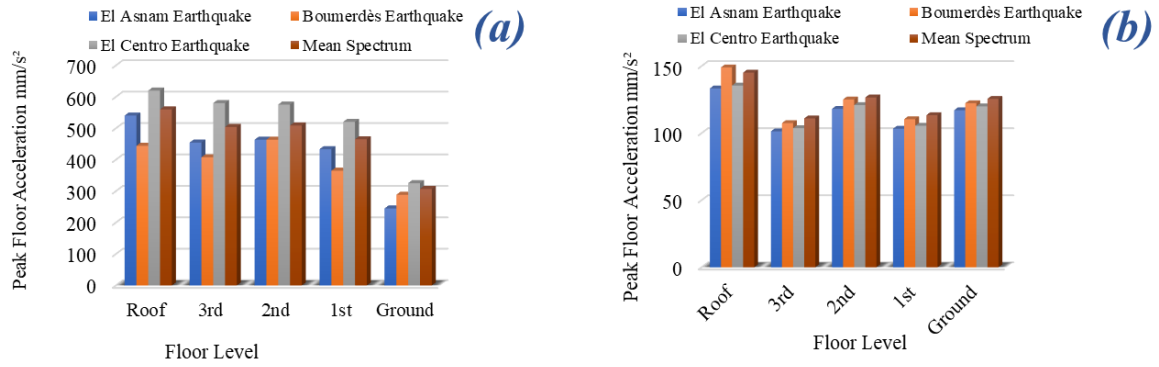


Fig. 5.20 Peak Floor Acceleration (PFA) for Block I: (a) Un-Retrofitted vs. (b) Retrofitted in X Directions.

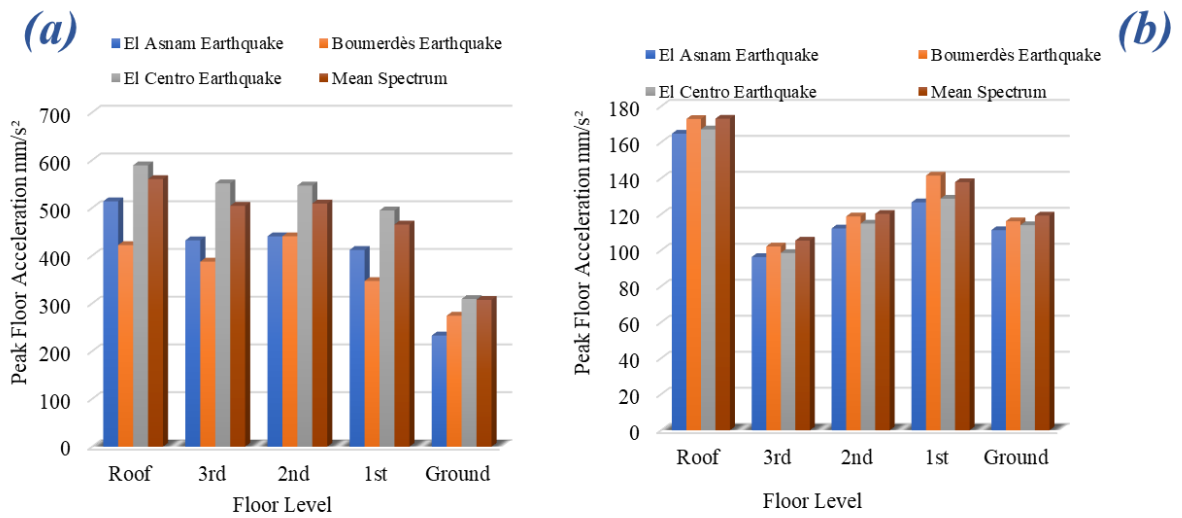


Fig. 5.21 Peak Floor Acceleration (PFA) for Block I: (a) Un-Retrofitted vs. (b) Retrofitted in Y Directions.

C. Displacement profiles

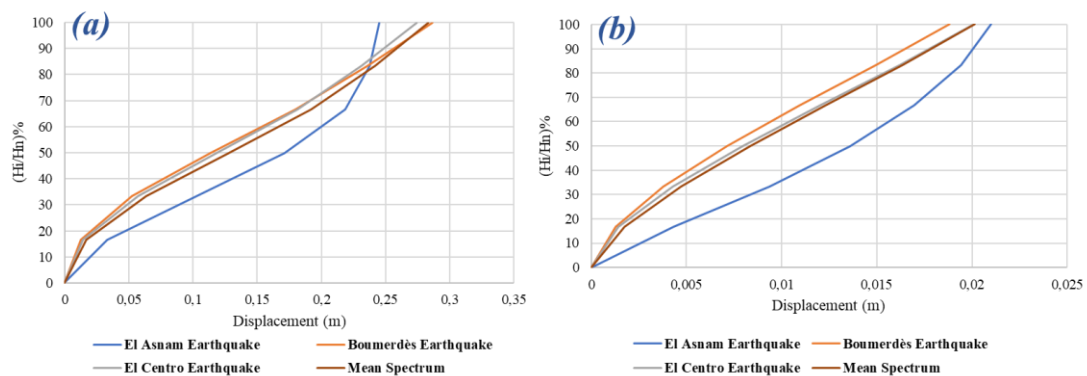


Fig. 5.22 Displacement Profiles for Block I: (a) Un-Retrofitted vs. (b) Retrofitted Under Seismic Loading.

The results of the seismic performance analysis for Block I after retrofitting with the Hybrid SMA-FRP system demonstrate significant improvements in load-bearing capacity, ductility, energy dissipation, and overall seismic resilience in both the X and Y directions. The capacity curves show that the retrofitted structure surpasses the original design specifications in both

directions, with the X-direction reaching a peak base shear of 800 kN at 100 mm displacement and the Y-direction achieving 900 kN at 125 mm, both demonstrating improved stiffness, delayed yielding, and enhanced post-peak behavior. This indicates better energy dissipation and improved joint strength, which are critical for reducing seismic damage. The plastic hinge distribution reveals that the retrofitted structure has shifted hinge formation to the Immediate Occupancy (IO) performance level, with predominantly ductile behavior in both directions, thus preventing brittle failure and ensuring energy dissipation through SMA braces and CFRP wraps. The inter-story drift ratios show that the retrofitted structure remains well below the Serviceability Performance Limit (SPL), highlighting an increase in lateral stiffness, flexural capacity, and overall stability. The Pushover Analysis confirms that the retrofitted structure has a higher peak base shear and improved ductility compared to the pre-retrofit condition. Additionally, Nonlinear Time History Analysis (NTHA) results demonstrate a substantial reduction in residual displacements and inter-story drifts across multiple earthquake simulations, including the El Asnam, Boumerdès, and El Centro earthquakes, verifying the effectiveness of the retrofit in minimizing permanent deformations. The Peak Floor Acceleration (PFA) results show that the retrofitted structure experiences significant reductions in accelerations across all floor levels, especially in the upper stories, indicating a marked improvement in lateral stiffness and energy dissipation, reducing the risk of non-structural damage. The displacement profiles further highlight a dramatic reduction in lateral displacements, with the retrofitted structure exhibiting more consistent and predictable responses to seismic forces. As evidenced by SMA braces and CFRP wraps, energy dissipation was significantly improved, enhancing the structure's ability to absorb and dissipate seismic energy efficiently. The results confirm that the Hybrid SMA-FRP retrofitting system has successfully enhanced the structure's seismic resilience, pushing it beyond its original design limits, ensuring compliance with performance standards, and achieving the Immediate Occupancy (IO) performance criterion, with minimal damage and increased safety during seismic events.

3.3. Rehabilitation Technique for Block II Using Fluid Viscous Dampers in Combination with Shear Walls

The combination of viscous dampers and shear walls provides a robust solution to address the seismic vulnerabilities identified in Block II. Viscous dampers will provide energy dissipation, reduce seismic vibrations, and mitigate inter-story drifts and soft-story effects. On the other hand, shear walls will significantly enhance the lateral stiffness and strength, providing a stabilizing effect under seismic loading. This hybrid system is ideal for addressing the

vulnerabilities of Block II, such as soft-story behavior, brittle failure mechanisms, and insufficient lateral stiffness.

Recent studies have shown that viscous dampers effectively reduce residual displacements and seismic accelerations, while shear walls strengthen the overall lateral load resistance. For instance, Yıldız et al. [68] conducted a case study on a school building, demonstrating that viscous dampers significantly reduce seismic response and improve structural resilience. Similarly, a study on optimizing viscous damper parameters in frame-shear wall structures highlighted their role in reducing inter-story drift and improving seismic performance [69]. De Domenico et al. [70] comprehensively reviewed viscous damper design strategies, emphasizing their effectiveness in seismic retrofitting. Additionally, a comparative study on fluid viscous dampers and base isolation showed that combining viscous dampers with shear walls significantly reduces structural response, making it an effective retrofitting solution [71]. Optimal Design and Distribution of Viscous Dampers for Shear Building presented an optimal design method for viscous dampers, demonstrating their effectiveness in reducing top-floor displacements and improving seismic resilience [72]. Zhou et al. [73] discussed the distribution and effectiveness of fluid viscous dampers in multi-story buildings, emphasizing their role in energy dissipation and seismic performance improvement [6]. Finally, Aydin et al. [74] focused on the optimal placement of viscous dampers in planar structures, highlighting their effectiveness in seismic retrofitting and energy dissipation.

This combination has been proven to work well in retrofitting buildings with soft-story behavior, ensuring improved seismic resilience and compliance with Algeria's seismic code RPA 99/2003.

3.3.2. Objectives of Rehabilitation

X-Direction:

Enhance the stiffness and strength of lower-story columns and the overall lateral load-carrying capacity to reduce excessive inter-story drift; Use viscous dampers to reduce seismic vibrations, thus improving the post-peak behavior and preventing brittle failure; Strengthen beam-column joints and critical sections to reduce the risk of brittle failures and increase flexural and shear capacity.

Y-Direction:

Target mid-height columns where plastic hinges are concentrated during seismic loading, improving the lateral stiffness and reducing the risk of structural failure; Enhance the structure's ability to absorb seismic energy, improving the overall performance and ensuring that it can

withstand seismic forces more effectively; Increase the capacity to meet seismic demands by strengthening mid-height elements and adding shear walls for improved lateral resistance.

3.3.3. Modeling the Fluid Viscous Dampers and Shear Walls in ETABS

3.3.3.1. Material Properties for Hybrid System

A. Fluid Viscous Dampers

Fluid Viscous Dampers (FVDs) are passive energy dissipation devices that generate a damping force by moving a piston through a viscous fluid. The fluid's viscosity, piston design, and damper geometry determine its mechanical properties. FVDs are widely used in seismic and wind applications due to their ability to dissipate energy without adding stiffness to the structure.

Key Mechanical Properties

The mechanical properties of FVDs are characterized by their force-velocity relationship, damping exponent, and energy dissipation capacity. These properties are critical for designing dampers that can effectively reduce structural responses during dynamic events.

Force-Velocity Relationship: The damping force generated by an FVD is a function of the velocity of the piston movement. The relationship is given by:

$$F = C * V^\alpha \tag{5.1}$$

Where:

F = Damping force (kN)

C = Damping constant (kN·(s/m))

V = Velocity of the piston (m/s)

α = Damping exponent (typically between 0.2 and 2.0)

For seismic applications, α is usually in the range of **0.3 to 0.5**.

Damping Exponent (α): The damping exponent determines the nonlinearity of the damper's force-velocity relationship. A lower α (e.g., 0.3–0.5) results in higher energy dissipation per cycle, while a higher α (e.g., 1.0) results in a linear force-velocity relationship.

Energy Dissipation: FVDs dissipate energy by converting mechanical energy into heat. The energy dissipated per cycle is the area under the force-displacement hysteresis loop. This energy dissipation reduces the demand for structural elements during seismic or wind events.

Transformation Behavior: Unlike SMAs, FVDs do not exhibit phase transformations. Instead, their behavior is purely viscous, meaning the damping force is directly related to the velocity of the piston movement.

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The following **Table 5.17** outlines all the necessary properties and configurations required to model FVDs effectively in ETABS. These values were derived from the reference study by Zhang et al. [75], which thoroughly explored the mechanical modeling of FVDs under various conditions.

Table 5.17 Properties and Configurations for Modeling Fluid Viscous Dampers (FVDs) in ETABS.

Property/Configuration	Details
Link Type	Damper-Exponential (Fluid Viscous Dampers)
Force-Velocity Relationship	$F = C * V^\alpha$
Damping Constant (C)	547,13 (kN·(s/m))
Velocity Exponent (α)	0,4
Series Spring Constant (K)	350,2536 (kN/m)
Mass and Weight	Leave as zero or assign a small value for numerical stability
Nonlinearity	Enable nonlinear properties for U1 (translational direction).

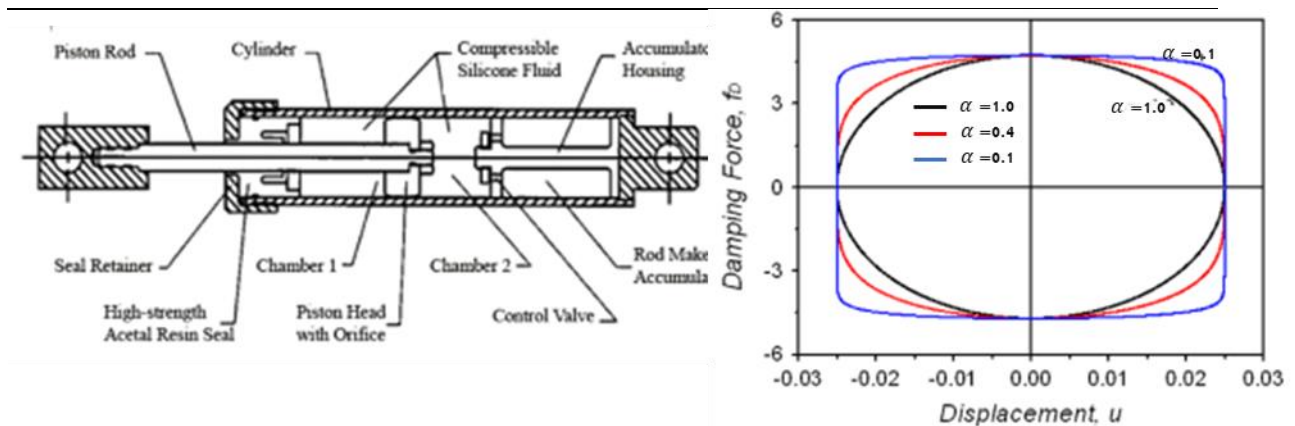


Fig. 5.23 Internal Components and Force-Displacement Behavior of (FVDs).

B. Shear walls

For the configuration of the shear walls, we have chosen to start with the minimum sections proposed by the RPA99/2003 to ensure compliance with regulatory requirements and to provide a practical and robust design. The dimensions of the wall are defined according to **Articles 7.7.1** and **7.7.3.2** of the code [3], while the mechanical properties of the materials have been selected based on commonly available industry standards. This includes using concrete with a minimum compressive strength of 25 MPa and high-strength reinforcing steel FE500 for both longitudinal and transverse reinforcements, ensuring optimal performance in terms of strength and ductility.

Table 5.18. Minimum Dimensions and Sections of Shear Walls.

Property	Value/Calculation	Reference

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Thickness (a)	$a=15\text{cm}$	Article 7.7.1 (RPA99/2003)
Length (l)	$l=4\cdot a=4\cdot 15\text{cm}=60\text{cm}$	Refer to Figure 7.7 (RPA99/2003)
Concrete Section (S_{concrete})	$S_{\text{concrete}}=a\cdot l=15\cdot 60=900\text{cm}^2$	Calculated
Longitudinal Reinforcement Section ($S_{\text{longitudinal}}$)	$0.15\% \cdot S_{\text{concrete}}=0.0015\cdot 900=1.35\text{cm}^2$	Article 7.7.3.2 (RPA99/2003)
Transverse Reinforcement Section ($S_{\text{transverse}}$)	$0.25\% \cdot S_{\text{concrete}}=0.0025\cdot 900=2.25\text{cm}^2$	Article 7.7.3.2 (RPA99/2003)

Table 5.19 Mechanical Properties of Materials.

Property		Value
Concrete	Compressive Strength	25MPa
	Modulus of Elasticity E	32164MPa
	Shear Modulus G	13402MPa
	Poisson's Ratio (ν)	0.2
	Density (ρ)	2400 kg/m ³
Steel	Yield Strength	500MPa
	Ultimate Tensile Strength	550MPa
	Modulus of Elasticity E_s	200,000MPa
	Poisson's Ratio (ν)	$\nu=0.3$
	Density (ρ)	7850kg/m ³

3.3.3.2.Strategy for Applying FVDs and Shear Walls in Block II

A hybrid retrofitting technique combining Fluid Viscous Dampers (FVDs) and Shear Walls has been developed to address the unique seismic vulnerabilities of Block II. This approach directly targets critical weaknesses, such as inadequate stiffness in the X-direction, concentrated plastic hinges at mid-height stories, and weak beam-column joints prone to brittle failure. By strategically integrating FVDs to dissipate energy and control dynamic forces and L-shaped shear walls to enhance lateral stiffness and stability, the strategy ensures a robust seismic response while meeting Algeria's RPA 99/2003 seismic code requirements. This combination not only improves structural resilience but also optimizes space utilization and simplifies construction, effectively mitigating collapse risks and enhancing ductility across all stories.

Table 5.19 Installation Strategy for FVDs and Shear Walls in Block II.

Technique	Element/Location	Application	Purpose	Justification
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Shear Walls	Corners (All Stories)	- Install L-shaped shear walls at the building's four corners symmetrically in both X and Y directions, extending continuously from the ground to the top story.	- Provide lateral stiffness and stability in all directions while maintaining uniform load paths and minimizing drift ratios.	- Simplifies structural design, enhances seismic resistance and reduces torsional effects.
Fluid Viscous Dampers (FVDs)	Between Shear Walls (Ground to Third Floors)	- Install FVDs in diagonal configurations in central bays, symmetrically in both X and Y directions.	- Dissipate seismic energy, reduce inter-story drifts, and control deformation at mid-height.	- Diagonal placement ensures optimal energy dissipation and directly addresses dynamic forces and mid-height vulnerabilities, particularly in the X-direction.
	Roof Level	- Install FVDs in chevron configurations at the roof level.	- Minimize vibrations and residual displacements at the top of the structure.	- Ensures damping efficiency across the full height of the building.

3.4. Seismic Analysis Methodology

This section outlines the seismic analyses performed to evaluate the retrofitted Block II of the Urology Pavilion at CHU Mustapha Pacha. Similar to Block I, pushover analysis and nonlinear time history analysis (NTHA) were conducted in ETABS. These analyses provide insights into the static and dynamic seismic performance of Block II after implementing the hybrid FVD-Shear Wall retrofitting system.

For detailed parameters and methodologies used in these analyses, please refer to **Table 5.16** ("*Summary of Seismic Performance Evaluation Methods for Block I*"), as the same methods were applied to both blocks with adjustments for specific design conditions in Block II.

3.4.1. Seismic Performance Results and Evaluation of Retrofitted Block II

3.4.1.1. Pushover Analysis Results

A. Capacity Curve:

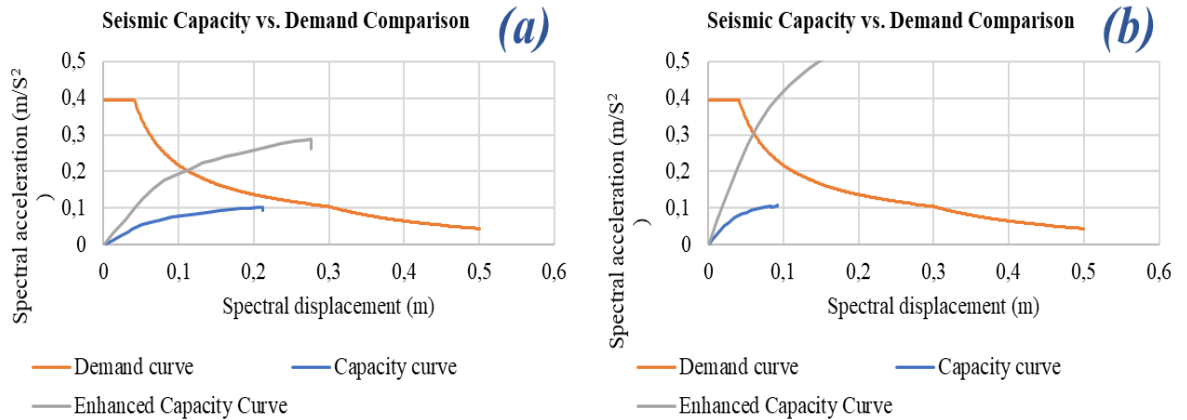


Fig. 5.27 Seismic Capacity and Enhanced Capacity vs. Demand Comparison for Block II: X-Direction (a) vs. Y-Direction (b).

3.4.1.2. Nonlinear Time History Analysis (NTHA) Results

A. Residual displacement

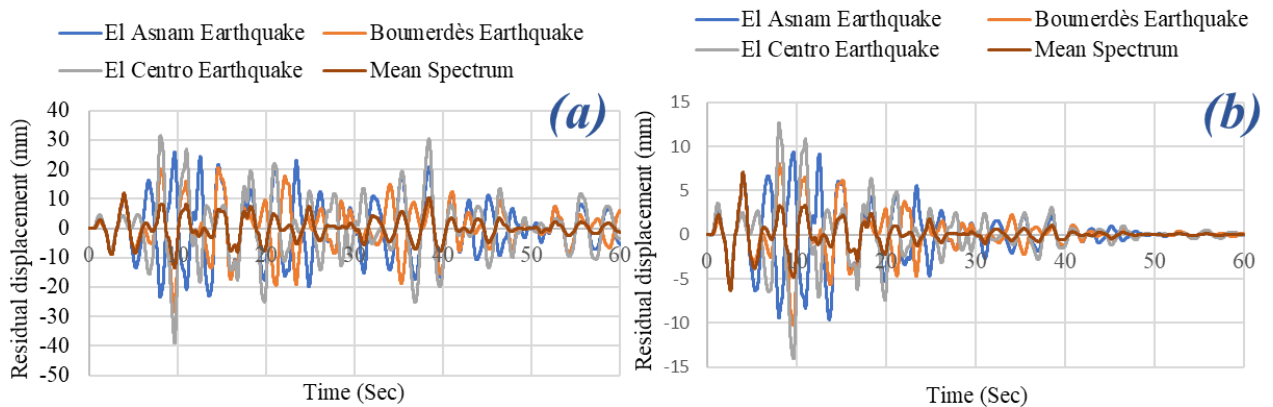


Fig. 5.28 Residual Displacement Time Histories for Block II in the X-Direction: (a) Un-Retrofitted vs. (b) Retrofitted.

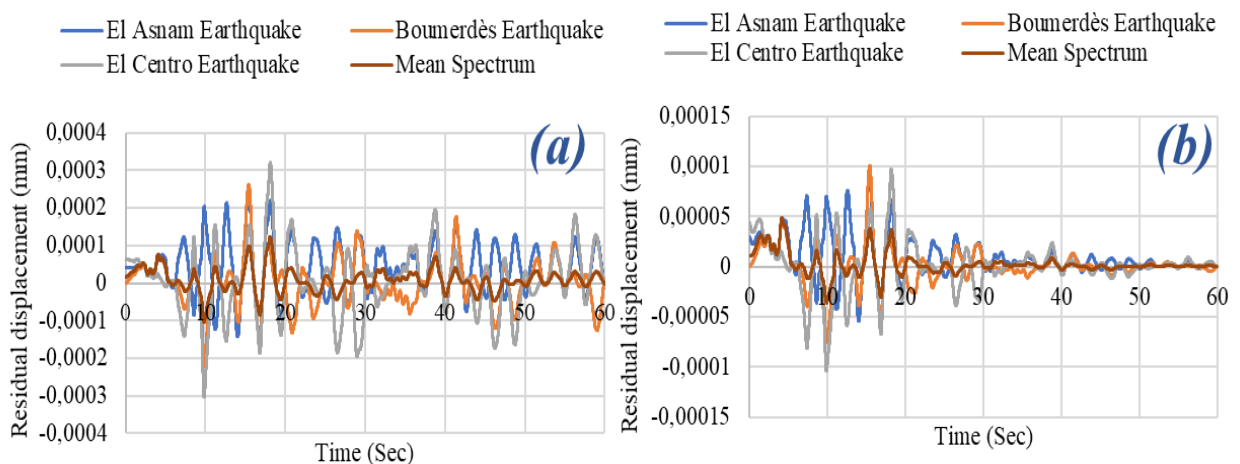


Fig. 5.29 Residual Displacement Time Histories for Block II in the Y-Direction: (a) Un-Retrofitted vs. (b) Retrofitted.

B. Peak floor acceleration

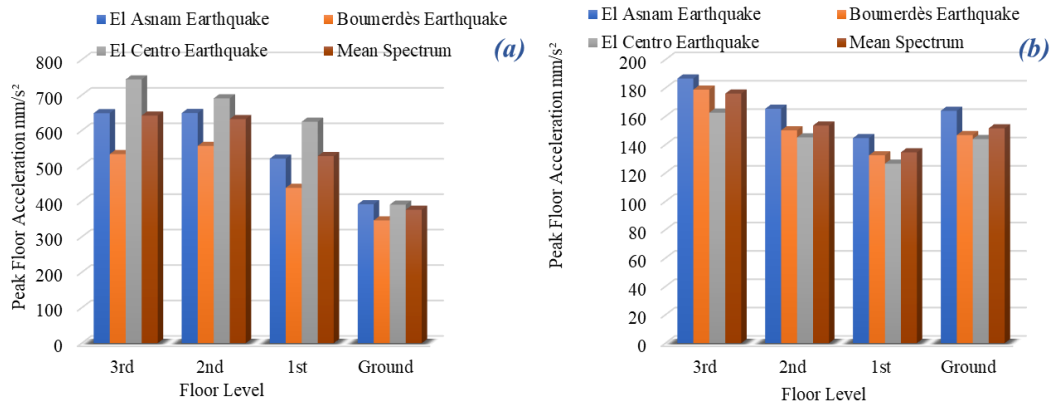


Fig. 5.30 Peak Floor Acceleration (PFA) for Block II: (a) Un-Retrofitted vs. (b) Retrofitted in X Directions.

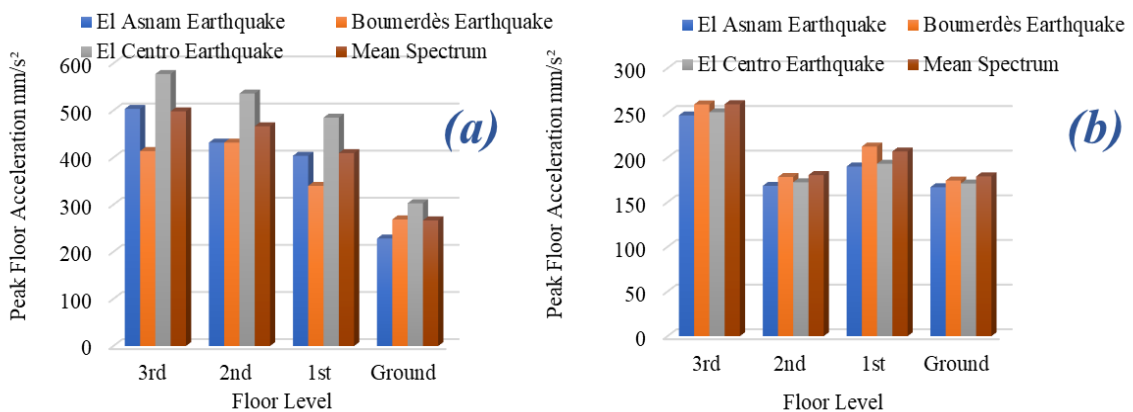


Fig. 5.31 Peak Floor Acceleration (PFA) for Block II: (a) Un-Retrofitted vs. (b) Retrofitted in Y Directions.

Step 01. Displacement profiles

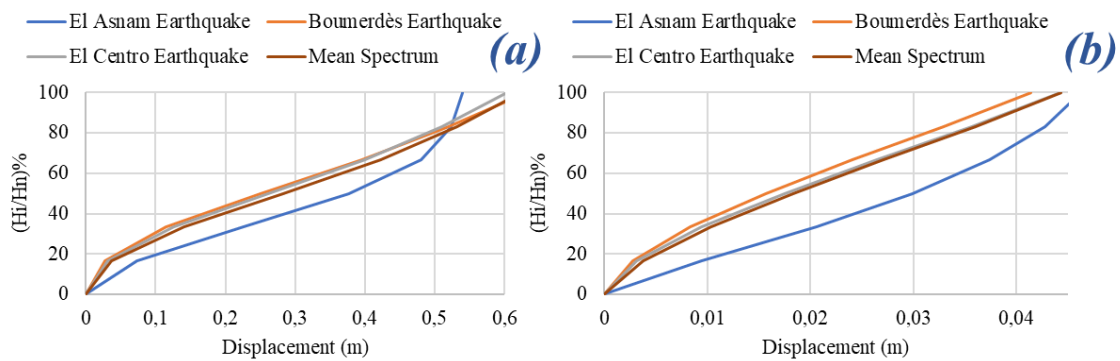


Fig. 5.32 Displacement Profiles for Block II: (a) Un-Retrofitted vs. (b) Retrofitted Under Seismic Loading.

The post-rehabilitation results for Block II of the Urology Pavilion at CHU Mustapha Pacha reveal a transformative improvement in seismic performance, effectively addressing its critical vulnerabilities through the integration of L-shaped shear walls and Fluid Viscous Dampers (FVDs). The shear walls, strategically placed at the building's corners, significantly enhanced lateral stiffness, minimizing excessive inter-story drift ratios and reducing deformation demands on beam-column joints, particularly in the X-direction where brittle failure

mechanisms were previously dominant. Simultaneously, the FVDs, installed symmetrically in central bays and at the roof level, provided exceptional energy dissipation, mitigating plastic hinge concentration and improving ductility, especially in mid-height stories where vulnerabilities were most pronounced. Pushover analysis confirmed these enhancements, with peak base shears increasing to ~900 kN (X-direction) and ~950 kN (Y-direction), surpassing pre-rehabilitation capacities and intersecting seismic demand curves. Plastic hinge distributions shifted dramatically from Collapse Prevention (CP) to Life Safety (LS) and Immediate Occupancy (IO) hinges, reflecting reduced brittle failures and improved energy dissipation. Inter-story drift ratios, previously exceeding allowable limits, were controlled to within serviceability thresholds, particularly addressing mid-height vulnerabilities in the X-direction. Nonlinear Time History Analysis (NTHA) further validated these improvements, showing drastic reductions in residual displacements and peak floor accelerations, especially in upper stories, as the FVDs effectively absorbed seismic energy. Displacement profiles became more uniform, with lateral displacements significantly reduced, ensuring structural stability during seismic events. The retrofitted structure now achieves Immediate Occupancy (IO) performance levels, meeting Algeria's seismic code (RPA 99/2003) requirements. Combining shear walls for lateral stiffness and FVDs for energy dissipation has effectively addressed soft-story effects, weak beam-column joints, and insufficient ductility, ensuring enhanced seismic resilience, minimal damage, and functional safety post-earthquake. This hybrid retrofitting strategy not only safeguards life safety and structural integrity but also provides a robust, scalable solution for improving the seismic performance of existing reinforced concrete structures in high-risk seismic zones like Algeria.

Step 04: Post-Rehabilitation Validation

Following the earlier steps of the Algeria-Specific Seismic Assessment Framework, the Post-Rehabilitation Validation step confirms the effectiveness of the retrofitting measures applied to Block I and Block II. This phase ensures that the rehabilitated structures meet the desired seismic performance benchmarks, such as Immediate Occupancy (IO) or Life Safety (LS), while addressing the vulnerabilities identified in the assessment phases. Through rigorous validation techniques, we evaluate the improved behavior of both blocks under seismic demands, verifying that the implemented strategies align with theoretical predictions and practical objectives.

4.1. Results for Block I

- ✚ The retrofitted Block I achieved Immediate Occupancy (IO) performance, ensuring the building remains safe and fully functional immediately after an earthquake, with no need for major repairs.
- ✚ Plastic hinges are now limited to ductile-controlled zones, such as beam ends and column bases, with no hinges forming in critical joints. This demonstrates the effectiveness of CFRP wraps in strengthening joints and improving confinement.
- ✚ Inter-story drift ratios were significantly reduced and remained within the acceptable limits (<0.01), ensuring compliance with RPA 99/2003 seismic code requirements.
- ✚ Residual displacements were minimal, validating the self-centering properties of SMA braces, which allow the structure to return to its original position after seismic events.
- ✚ SMA braces successfully absorbed seismic energy, reducing demands on other structural components and enhancing the overall ductility of the structure.
- ✚ Field observations and case studies of similar retrofitted buildings, such as those presented by Xue et al. [76] [77] in their experimental studies on RC beams shear-strengthened and flexural-strengthened with FRP/SMA composites, and Joshi and Vivek [78] in their compilation of case studies on FRP techniques for seismic retrofitting, confirm the elimination of soft-story behavior and brittle failure mechanisms. These findings align well with theoretical predictions and validate the effectiveness of the retrofitting strategies applied to Block I.

4.2. Results for Block II

- ✚ Achieved Immediate Occupancy (IO) performance under design-level seismic loads, ensuring the building remains safe and functional without requiring major repairs.
- ✚ Plastic hinges are limited to ductile zones, such as the bases of shear walls and the ends of beams, with no hinges forming in critical joints or mid-height columns.
- ✚ Inter-story drift ratios are significantly reduced, remaining well below the SPL limit of 0.01, ensuring compliance with RPA 99/2003.
- ✚ Residual displacements are minimized due to the enhanced energy dissipation provided by fluid viscous dampers (FVDs).
- ✚ FVDs effectively reduced seismic vibrations and inter-story drifts, ensuring the structural components remain within elastic or minimally inelastic ranges.
- ✚ Post-earthquake inspection data and comparisons with similarly retrofitted buildings, such as the seismic retrofitting of a school building using viscous dampers by Yıldız et al. [79], the comparative evaluation of shear walls and fluid viscous dampers in public school buildings by Alhamdany and Dilsiz [80], and the state-of-the-art review on

damper placement and subsystem stiffness by Ahmed et al. [81], validated the hybrid system's ability to mitigate plastic hinge concentration, excessive drifts, and collapse risks, achieving superior seismic performance.

Step 05: Decision-Making and Final Evaluation

The final step in the Algeria-Specific Seismic Assessment Framework evaluates the post-rehabilitation seismic performance of Block I and Block II. This phase synthesizes all the data collected during the rehabilitation process to assign each block a seismic performance classification. The classifications—based on performance benchmarks such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)—determine the buildings' safety, functionality, and resilience in seismic events, ensuring they meet the standards outlined in RPA 99/2003.

5.1. Seismic Performance Classification

Based on post-rehabilitation validation and comprehensive analysis, the following classifications and insights were determined:

A. Block I: Immediate Occupancy (IO)

The retrofitted Block I meets the Immediate Occupancy performance level, ensuring it remains safe and fully functional after seismic events.

Key Indicators:

- Minimal structural damage, with plastic hinges restricted to ductile zones like beam ends and column bases.
- Inter-story drifts remain well below <0.01 , complying with seismic standards.
- Residual displacements are negligible, validating the effectiveness of SMA braces in providing self-centering capabilities.

B. Block II: Immediate Occupancy (IO)

The hybrid retrofitting of Block II with shear walls and fluid viscous dampers (FVDs) has enabled it to achieve the Immediate Occupancy classification.

Key Indicators:

- Improved lateral stiffness and energy dissipation capacity, reducing inter-story drifts and seismic forces.
- Plastic hinges form only in controlled zones, such as the bases of shear walls and beam ends, and there are no critical failures in joints or columns.
- FVDs effectively reduced vibrations and residual deformations, ensuring structural functionality post-earthquake.

5.2. Final Evaluation and Decision-Making

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The final decision regarding the seismic resilience of Block I and Block II includes the following conclusions and actionable steps:

A. Block I: Cleared for Immediate Occupancy, requiring only periodic inspections to ensure the continued effectiveness of retrofitting measures; Functional recovery is immediate, with minimal to no operational disruptions after seismic events.

B. Block II: Cleared for Immediate Occupancy, meeting all performance objectives and seismic safety standards; Enhanced energy dissipation and stiffness ensure safety and functionality even under design-level earthquakes.

C. Recommendations for Ongoing Monitoring and Maintenance

A. Routine Inspections:

- ∞ Conduct periodic visual and nondestructive tests to ensure no deterioration of retrofitted components.
- ∞ Regular monitoring of CFRP wraps, SMA braces, and FVD systems for wear or loss of performance.
- ∞ Structural Health Monitoring (SHM):
- ∞ Implement SHM systems for long-term tracking of seismic performance, especially in critical elements such as beam-column joints and shear walls.

B. Post-Event Inspections:

- ∞ Schedule immediate inspections after seismic events to confirm that the buildings remain in the Immediate Occupancy category.
- ∞ Regulatory Compliance and Future Use
- ∞ Both blocks fully comply with RPA 99/2003 seismic regulations and are deemed fit for re-occupancy with no additional retrofitting required.
- ∞ Their Immediate Occupancy classification ensures they are suitable as functional buildings with enhanced seismic resilience, safeguarding occupants and infrastructure.
- ∞ This final step confirms the seismic safety and functionality of Block I and Block II, ensuring their resilience against future seismic events while meeting all regulatory and performance standards.

5.3.2.2 Case Study 2: Residential Building in Ibn Khaldoun Housing Estate (1200 Housing Units), Boumerdès, Algeria.

Step 01: Data Collection

A. General Building Information

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Fig 5.33 Location of the Case Study 3.

Table 5.20. Information for Ibn Khaldoun Housing Estate (1200 Housing Units).

Category	Details	
1. Location and Seismic Zone	Geographic Location	Located in Ibn Khaldoun Housing Estate, Boumerdès, Algeria, a region with seismic history.
	Seismic Zone	Boumerdès is classified under Seismic Zone III as per RPA 99/2003, indicating a high seismic risk area.
2. Building Function	Purpose	Residential building, part of a 1200 Housing Units project.
3. Construction Era and Practices	Importance	Non-critical infrastructure; seismic resilience is vital for resident safety during seismic events.
	Year of Construction	Built between 1975 and 1980, before the RPA 99/2003 seismic codes.
	Design Standards Applied	Constructed under older seismic standards, which did not account for modern seismic design principles, resulting in vulnerabilities.



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4.	Dimensio ns	Overall plan dimensions: 56.93m × 35.21m. Total height: 15.5m (ground floor + three stories).
	Load- Bearing Elements	Building dimensions: 17.95 m × 12.00 m, total height: 15.3 m (Ground floor + 4 floors).

Fig 5.34 Architectural Facade of the Residential Building.

B. Structural Data Collection

Table 5.20. Detailed Structural and Site Data for Ibn Khaldoun Housing Estate.

Details	
1. Building Geometry and Layout	Dimensions: 17.95 m × 12.00 m. Total height: 15.3 m (Ground floor + 4 floors). Structural System: Reinforced concrete moment-resisting frame system with regularly spaced columns.
2. Plates/Floors	Flooring: Solid slabs, 20 cm thick.
3. Column Types	Edge Columns: 20 cm × 40 cm. Central Columns: 20 cm × 50 cm.
4. Beam Dimensions	All beams: 20 cm × 40 cm.
5. Material Properties:	
Concrete	Concrete: Based on NDT results (ultrasonic pulse velocity and Schmidt hammer tests). Steel Reinforcement: Refer to Table 5.21 for detailed steel reinforcement properties.
Steel Reinforcement	Refer to Table 5.22 for reinforcement details for columns and beams.
6. Reinforcement Detailing for Columns and Beams	(See Table 5.23 for reinforcement details for columns and beams)
7. Beam-Column Joint Connections.	See Table 5.24
8. Site-Specific Data Collection	Soil Properties (See Table 5.25 for detailed soil properties)
9. Seismic Hazard Data for the Site	See Table 5.26
10. Historical Seismic Data	(Past Earthquakes: Reference to earthquakes like El Asnam (1980) and Boumerdès (2003), affecting the region. Refer to Table 5.27 for detailed historical seismic data and impact on the structure.

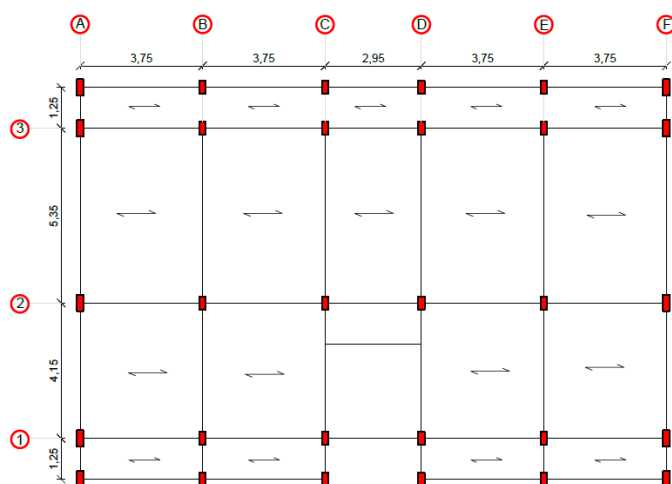


Fig 5.35 Structural Layout Plan of the Residential Building.

Table 5.21 Material Properties of Concrete.

Property	Value
Compressive Strength (f_c)	15 MPa
Modulus of Elasticity (E)	27,126 MPa
Poisson's Ratio (ν)	0.2
Density (ρ)	2400 kg/m ³

Table 5.22. Steel Reinforcement Properties.

Property	Value
Reinforcement Grade	FeE235
Yield Strength (f_y)	266.66 MPa
Ultimate Tensile Strength	347.82 MPa
Elastic Modulus (E)	210,000 MPa
Poisson's Ratio (ν)	0.3
Corrosion Level	Moderate (observed corrosion of reinforcement bars)

Table 5.23. Reinforcement Details for Columns and Beams.

Element	Level	Reinforcement Details
Columns	Ground Floor	Longitudinal Bars: 4 Ø14mm Stirrups: Ø8 mm @ 300 mm spacing
	1st–3rd Floors	Longitudinal Bars: 4 Ø12mm Stirrups: Ø8 mm @ 250 mm spacing

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	4th–5th Floors	Longitudinal Bars: 4 Ø12mm
		Stirrups: Ø6 mm @ 250 mm spacing
Beams	All Levels	Top/Bottom Reinforcement: 2 Ø12 mm (top), 2 Ø12 mm (bottom)
		Stirrups: Ø6 mm @ 200 mm spacing

Table 5.24. Observations on Beam-Column Joint Connections

Aspect	Observation
Anchorage Length	Insufficient anchorage length, leading to reduced load transfer capabilities.
Bar Anchorage in Joints	Lack of proper anchorage within the joint region, causing slippage or failures.
Confinement Reinforcement	Inadequate confinement reinforcement in joints, reducing ductility and energy dissipation.
Joint Integrity	The structural integrity of joints compromised under seismic loads.

Table 5.25. Soil Properties

Property	Value/Details
Foundation Type	Shallow isolated footings
Soil Classification	S3 (Soft Soil) as per RPA 99/2003
Shear Wave Velocity (Vs)	200–400 m/s

Table 5.26. Seismic Hazard Data for the Site.

Property	Value/Details
Seismic Zone	Zone III (High Seismic Risk)
Peak Ground Acceleration (PGA)	0.35 g

Table 5.27. Historical Seismic Data and Impact on the Structure

Property	Details
Past Earthquakes	-Tlemcen Earthquake (1980) - Zemmouri Earthquake (2003)
Impact on Structure	- Severe damage to reinforced concrete and masonry structures, especially in the

Boumerdes region after the Zemmouri Earthquake 2003.

-Older buildings, especially those without seismic design, experienced significant failures.

C. Seismic Performance Evaluation

Table 5.28. Proposed Seismic Performance Levels (SPLs) for the Residential Building in Ibn Khaldoun Housing Estate.

Performance Level	Objective	Indicators
Life Safety (LS)	The building should ensure safety for occupants during and immediately after an earthquake, providing structural integrity and safe evacuation.	<ul style="list-style-type: none"> - No structural damage to critical elements (e.g., beams, columns, shear walls). - No significant damage to primary load-bearing elements (e.g., columns, beams, foundation). - Non-structural elements (e.g., partitions, windows) may experience minor damage but should not impair the overall functionality of the building.

Step 02: Structural Analysis Methods (Pre-Rehabilitation)

For the seismic performance evaluation of the Residential Building in the 1200 Housing Units, Boumerdes, the pushover analysis was selected as the primary structural analysis method, due to its practicality, efficiency, and ability to focus on critical issues within the building's structure:

- Pushover analysis captures the structure's nonlinear behavior, which is crucial for understanding its performance, especially given the building's age and the concrete's compressive strength of 15 MPa. This analysis method identifies potential areas of weakness, including deterioration of materials due to aging and damage sustained from previous seismic events, like the 2003 Zemmouri Earthquake.
- Failure Modes Identification: This analysis helps pinpoint potential failure modes, such as weak columns, insufficient beam-column joint reinforcement, and poor confinement reinforcement, which are common issues in buildings constructed in the late 1970s and early 1980s.

- **Nonlinear Performance:** Unlike linear static analysis, which assumes elastic behavior, pushover analysis takes into account the building's inelastic behavior under seismic loads. This approach is more appropriate for older structures like this one that may exhibit plastic deformations under lateral loads.
- **Nonlinear Dynamic Methods:** Although nonlinear dynamic methods such as time-history analysis are more precise, they are resource-intensive and require accurate ground motion data, which may not be available for this analysis stage. Therefore, pushover analysis is preferred as it provides valuable insights without the need for complex ground motion data.
- **Force-Displacement Curve:** By generating a force-displacement curve, pushover analysis evaluates the building's ability to meet Seismic Performance Levels (SPLs) such as Life Safety (LS) under seismic loading. It provides insights into how the building will perform in future earthquakes and whether it will likely remain intact or sustain significant damage.
- **Performance-Based Seismic Design:** The analysis aligns with performance-based seismic design principles, ensuring that structural performance can be directly tied to specific safety objectives and providing a clear path for necessary improvements.
- **Next Steps:** Pushover analysis provides essential outputs like capacity vs. demand and identifies failure mechanisms, which directly inform the next steps:
 - Vulnerability assessment
 - Capacity-demand comparison
 - Rehabilitation planning

2.1. Results from Pushover Analysis

A. Capacity Curve:

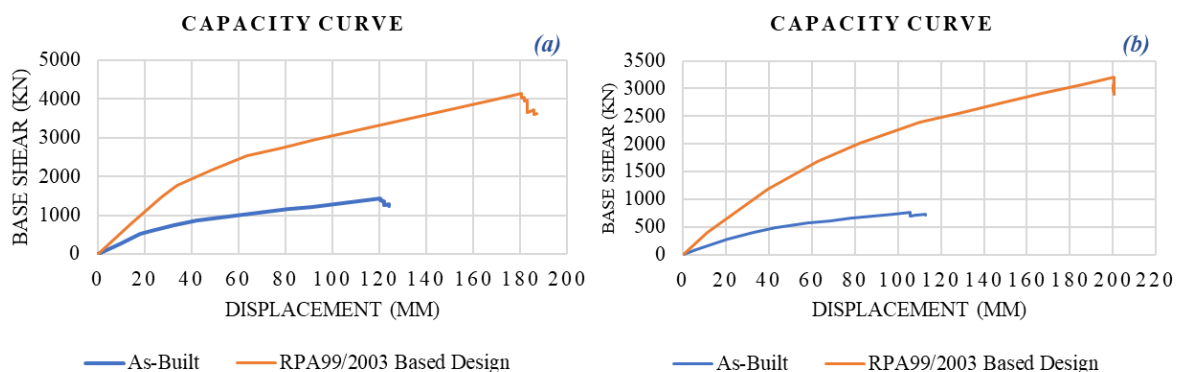


Fig 5.36. Capacity Curves: Actual vs. Design Performance in X and Y Directions.

B. Plastic Hinge Formation

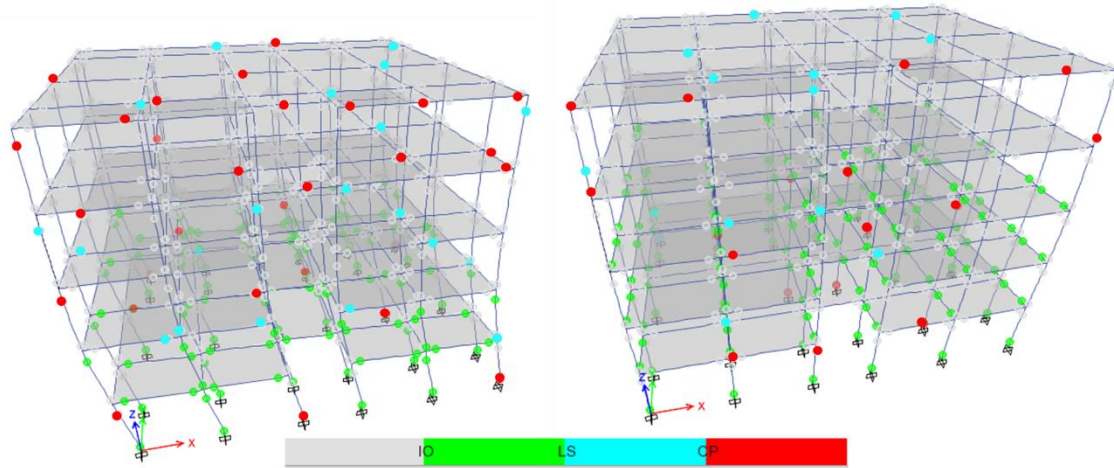


Fig 5.37. Plastic Hinge Distribution: X-Direction (a) vs. Y-Direction (b).

C. Inter-Story Drift Ratios

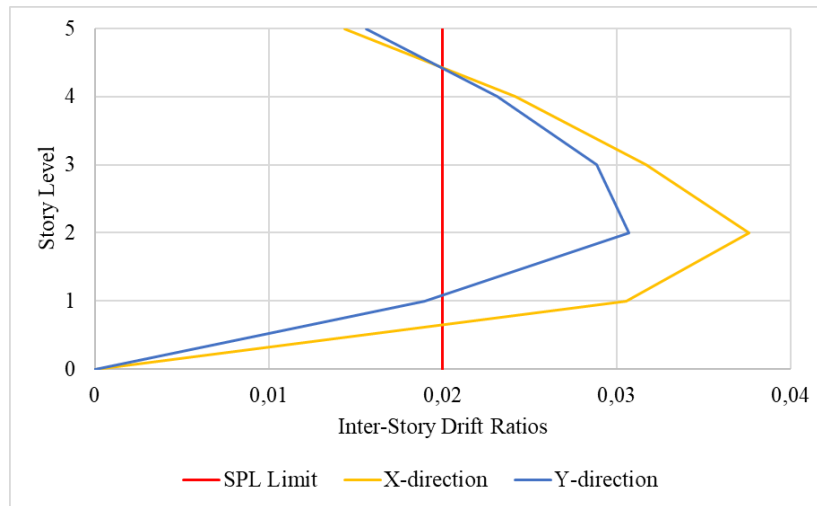


Fig 5.38. Inter-Story Drift Ratio Curves.

The pushover analysis of the Residential Building in the Cité des 1200 Housing Units clearly indicates several structural vulnerabilities when compared to current seismic design codes. The as-built capacity curve (blue) shows a base shear capacity of ~800 kN in the X-direction, significantly lower than the theoretical capacity calculated according to modern seismic regulations (RPA 99/2003), which is expected to be closer to 1,500 kN. This discrepancy reveals that the building's lateral force resistance is inadequate, especially in the X-direction, due to outdated design practices from the original construction period (1975-1980), before the implementation of modern seismic codes. The plastic hinge distribution analysis further supports this finding, with critical areas, particularly base columns and beam-column joints, exhibiting substantial plastic deformation. These areas, where plastic hinges transition from elastic (yellow) to yielding (orange) and finally to failure (red), highlight significant vulnerabilities. The base columns, in particular, are prone to failure under lateral seismic forces due to insufficient confinement and reinforcement detailing. In the X-direction, the plastic hinge

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formation is especially concentrated in the base columns and beam-column joints, suggesting that these elements are the weakest parts of the structure. Additionally, the inter-story drift ratio curves reveal that the building exceeds the acceptable drift limits of 0.02 (2%). In the X-direction, the drift ratios reach up to 0.05 (5%) in the upper stories, indicating excessive lateral displacement that could result in non-structural damage and compromise the building's functionality during seismic events. This behavior is consistent with the earlier identified vulnerabilities of inadequate reinforcement and poor detailing of joints, which amplify the risk of progressive collapse, particularly in the X-direction.

Retrofitting is essential to improving the building's seismic resilience. In the X-direction, strengthening base columns and beam-column joints and enhancing confinement reinforcement are recommended to increase stiffness and reduce inter-story drift. In the Y-direction, efforts should focus on reinforcing base columns and ensuring adequate joint detailing to maintain stability during severe seismic events. Addressing these deficiencies will help the building meet modern seismic safety standards and reduce the risk of catastrophic failure.

2.2. Vulnerability Assessment

The Residential Building in the Cité des 1200 Housing Units exhibits several structural and seismic vulnerabilities, as revealed by the pushover analysis, plastic hinge distribution, and inter-story drift ratios. These vulnerabilities, primarily stemming from outdated construction practices and the building's design before implementing modern seismic codes (RPA 99/2003), highlight critical areas that require immediate retrofitting. The identified weaknesses are categorized into structural, material, and seismic performance issues, as summarized below:

Table 5.29 Identified Vulnerabilities of the Building.

Vulnerability Type	Description	Impact
Base Columns	Insufficient reinforcement and weak confinement, particularly at the foundation level.	Early plastic hinge formation and high risk of failure under seismic loads.
Beam-Column Joints	Poor detailing and lack of proper confinement reinforcement in beam-column connections.	Premature joint failure leading to progressive collapse.
Upper-Level Columns	Insufficient stiffness and reinforcement in columns at higher floors.	Excessive lateral displacement and reduced ability to transfer seismic forces.
Low Stiffness in X-Direction	Flexible structural system in the longer X-direction due to lack of brace or shear walls.	Large displacements, high inter-story drifts, and inability to resist lateral loads.
Material Deficiencies	Concrete with low compressive strength ($f'_c = \sim 15$ MPa) and	Reduced load-bearing capacity and poor energy dissipation under seismic loading.

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	limited ductility due to construction era.	
Shear Failure in Beams	Vulnerability to shear failure in beams due to inadequate shear reinforcement.	Structural instability and compromised load transfer.
Inadequate Seismic Design	The building was constructed before modern seismic codes (e.g., RPA99/2003), with no consideration of ductility.	Overall poor seismic performance and inability to meet life safety criteria.
Inter-Story Drift in X-Direction	Excessive inter-story drift ratios (>5% in upper floors) in the X-direction.	Risk of story collapse and severe damage to structural and non-structural elements.
Lack of Redundancy	Limited alternative load paths in case of failure of primary load-bearing elements.	Increased risk of localized collapse propagating to global failure.

2.3. Seismic Capacity vs. Demand Comparison

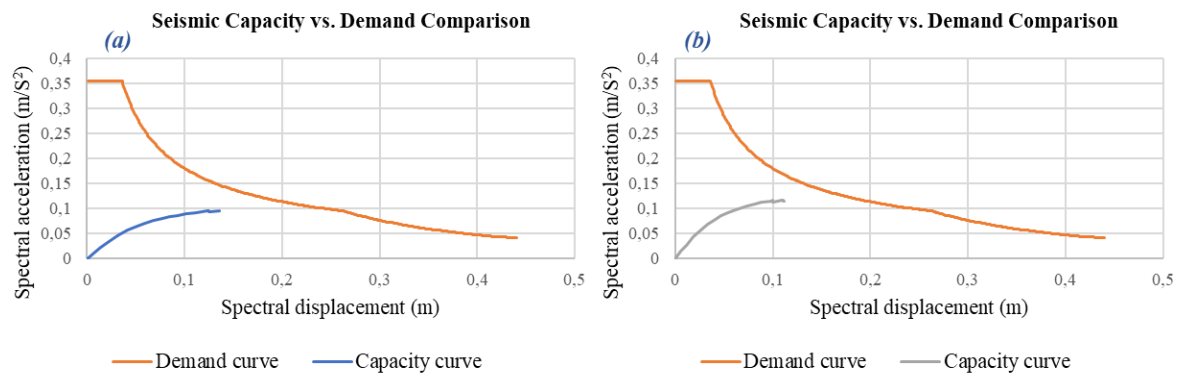


Fig 5.39. Seismic Capacity vs. Demand Comparison for: X-Direction (a) vs. Y-Direction (b).

The Seismic Capacity vs. Demand Comparison illustrates the disparity between the building's seismic resistance and the imposed seismic demand in both the X-direction (a) and Y-direction (b). In the X-direction, the demand curve significantly exceeds the capacity curve at all performance levels, reflecting the structure's severe deficiencies in resisting seismic forces. This aligns with observations of low stiffness, excessive inter-story drifts, and extensive plastic hinge formation in critical elements such as base columns and beam-column joints. While performing better, the Y-direction still demonstrates a noticeable gap between capacity and demand, particularly at higher force levels. This is consistent with the Y-direction's higher stiffness and improved base shear capacity but highlights persistent vulnerabilities in base columns and joints.

Overall, the comparison confirms that the building cannot meet the seismic demands prescribed for its performance objectives, particularly in the X-direction. Strengthening measures must prioritize enhancing lateral stiffness, increasing the ductility of base columns and beam-column

joints, and addressing material deficiencies to reduce the demand-capacity gap and ensure compliance with modern seismic safety standards.

Step 03: Rehabilitation Strategy Design

Following *Step 01: Data Collection* and *Step 02: Seismic Performance Evaluation*, the Building demonstrates critical structural deficiencies under seismic loading. Key issues include weak lateral resistance in the X-direction, localized vulnerabilities in base columns, and inadequate ductility in both the X- and Y-directions. The proposed rehabilitation strategy addresses these deficiencies through advanced strengthening techniques to ensure compliance with RPA 99/2003 and enhance the building's seismic resilience.

3.1. Damage Classification

Table 5.30. Damage Classification for the Residential Building in Ibn Khaldoun Housing Estate

Direction	Damage Classification	Severity	Reason	Structural Elements Affected
X-Dir	Severe Damage	Critical	Inability to meet seismic demands, excessive lateral displacement, poor column reinforcement	Base columns, beam-column joints, upper-story columns
Y-Dir	Moderate Damage	Moderate	Improved stiffness, localized hinge formation, insufficient overall capacity	Base columns, beam-column joints

Conclusion

The building exhibits:

- Severe Damage in the X-direction, attributed to low stiffness, widespread hinge formation in base columns and joints, and excessive inter-story drifts.
- Moderate Damage in the Y-direction, with localized vulnerabilities concentrated in base columns and beam-column joints.

3.2. Buckling-Restrained Braces (BRBs) with Ultra-High-Performance Concrete (UHPC) Casing for Seismic Rehabilitation of the Building

The Buckling-Restrained Brace (BRB) with Ultra-High-Performance Concrete (UHPC) casing is an innovative seismic rehabilitation technique designed to enhance structural resilience under seismic loading. BRBs resist both tension and compression forces without buckling, providing exceptional energy dissipation and ductility during cyclic events [82]. The steel core yields symmetrically in conventional systems, while steel or conventional concrete casings prevent global buckling. However, these casings face limitations such as excessive weight,

susceptibility to corrosion, and insufficient post-yield stiffness [83]. Replacing traditional casings with UHPC leverages its superior compressive strength (>150 MPa), crack resistance, and durability—properties critical for stabilizing BRB cores under high cyclic strains [84][85]. This hybrid system directly addresses vulnerabilities in aging reinforced concrete (RC) structures, such as excessive inter-story drifts, weak beam-column joints, and low ductility. In the Building, the X-direction exhibits significant lateral flexibility and inadequate stiffness, leading to excessive inter-story drifts that exceed 5%. BRBs with UHPC casings provide the lateral stiffness required to control these drifts while minimizing seismic demand on critical elements such as base columns and beam-column joints. Furthermore, the UHPC casing's ability to enhance energy absorption and delay hinge formation during seismic events can mitigate the poor confinement reinforcement in these elements. Recent studies validate UHPC's potential in confinement and load-bearing applications, Wu et al.[84] demonstrated UHPC's effectiveness as a precast plate casing for retrofitting GFRP-reinforced columns, highlighting its ability to resist buckling and distribute stresses uniformly. Yang et al. [86] developed double-stage yielding BRBs, emphasizing the need for high-strength casing materials to optimize multi-phase energy dissipation—a role UHPC uniquely fulfills. Barbagallo et al. [87] showed that advanced casings improve BRB performance in concentric braced frames by localizing damage in the steel core, a mechanism that UHPC's ductility and bond strength could further enhance.

By integrating UHPC into BRB casings, this system aligns with emerging trends in lightweight, high-performance seismic retrofitting, offering solutions to traditional casing drawbacks while improving lifecycle durability [88][89] This technique is particularly suitable for Case Study 2, as it addresses the structure's low stiffness, poor ductility, and high seismic demand in a targeted, cost-effective manner.

3.2.1. Objectives of Rehabilitation

X-Direction:

- Control drifts to within acceptable limits ($<2\%$) by improving lateral stiffness and energy dissipation.
- Increase the structure's capacity to resist seismic forces, addressing the low stiffness and high deformation observed in this direction.
- Prevent premature hinge formation in base columns and beam-column joints by redistributing seismic forces using BRBs with UHPC casing.
- Utilize BRBs to absorb seismic energy efficiently, minimizing demand on critical structural elements.

- Reduce shear and bending stresses on joints by offloading lateral forces through strategically placed braces.

Y-Direction:

- Address localized weaknesses in base columns to improve stability under seismic loading.
- Improve overall stiffness to maintain the structure's integrity during seismic events, even with moderate vulnerabilities in this direction.
- Minimize hinge formation in base columns and joints to ensure stability and reduce the risk of progressive damage.
- Use BRBs to enhance lateral load transfer, complementing the building's existing stiffness in the Y-direction.

3.2.2. Modeling Buckling-Restrained Braces (BRBs) with UHPC Casing in ETABS

3.2.2.1. Material Properties for Hybrid System

Buckling-restrained braces (BRBs) are specialized structural elements that provide high ductility and energy dissipation under seismic loading. A BRB consists of three main components: the core steel, the unbonding layer, and the outer casing.

- **Core Steel:** The core steel is the primary load-resisting element designed to yield symmetrically in tension and compression. This yielding behavior allows the BRB to effectively dissipate seismic energy.
- **Un-bonding Layer:** This layer separates the core steel from the outer casing to prevent interaction during axial deformation. It ensures that the core steel deforms freely while the casing remains intact.
- **Outer Casing:** The casing, made from conventional concrete, steel, or advanced materials like Ultra-High-Performance Concrete (UHPC), provides lateral support to the core. This casing prevents the core from buckling during compression and helps distribute the forces evenly.

Together, these components allow the BRB to maintain stability under extreme cyclic loading, providing superior lateral stiffness, ductility, and resilience. The integration of UHPC as the casing material enhances performance by offering exceptional compressive strength, crack resistance, and durability, making BRBs suitable for seismic retrofitting in vulnerable structures.

This study's Buckling-Restrained Brace (BRB) utilizes a steel core (grade S235JR, a structural steel with a nominal yield strength of 235 MPa) validated experimentally and numerically by Avci-Karatas et al. [90], selected for its stable hysteretic performance under cyclic loading. The

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S235JR steel core, tested in full-scale prototypes (BRB-SC4), exhibits a yield strength of 257

	Property	Value
1. Steel Core (S235JR)	Yield Strength (F_y)	257 MPa
	Ultimate Strength (F_u)	363 MPa
	Elastic Modulus (E)	195 GPa
	Yield Strain (ϵ_y)	38.21%
	Ultimate Strain (ϵ_u)	38.21%
	Poisson's Ratio (ν)	0.3
	Charpy Impact Energy	27 J at 20°C (per "JR" designation)
2. UHPC Casing	Compressive Strength (f_c)	138 MPa
	Tensile Strength (f_t)	9 MPa
	Elastic Modulus (E)	60 GPa
	Poisson's Ratio (ν)	0.18
	Density (ρ)	2480 kg/m ³
	Fracture Energy (G_f)	30,000 J/m ²
3. Filler Material (Mortar)	Compressive Strength	30MPa
	Elastic Modulus (E)	25 GPa
4. Interface Properties	Friction Coefficient (μ)	0.03

MPa, ultimate strength of 363 MPa, and ductility (38% strain capacity), ensuring reliable energy dissipation. The core is integrated with an Ultra-High-Performance Concrete (UHPC) casing to enhance buckling resistance and durability, validated by Shafieifar et al. [91]. UHPC provides exceptional mechanical properties, including compressive strength exceeding 150 MPa, tensile strength of 8–12 MPa, and fracture energy >30,000 J/m², reinforced by steel fibers (1–3% by volume) for crack resistance. Its dense microstructure ensures robust lateral confinement of the steel core, mitigating buckling risks and distributing stresses uniformly, while low permeability reduces environmental degradation. By replacing traditional casings with UHPC, the BRB achieves a lightweight, high-strength design, optimizing seismic resilience in retrofitted structures under extreme deformations.

Table 5.31. Material Properties of Buckling-Restrained Braces (BRBs) with UHPC Casing.

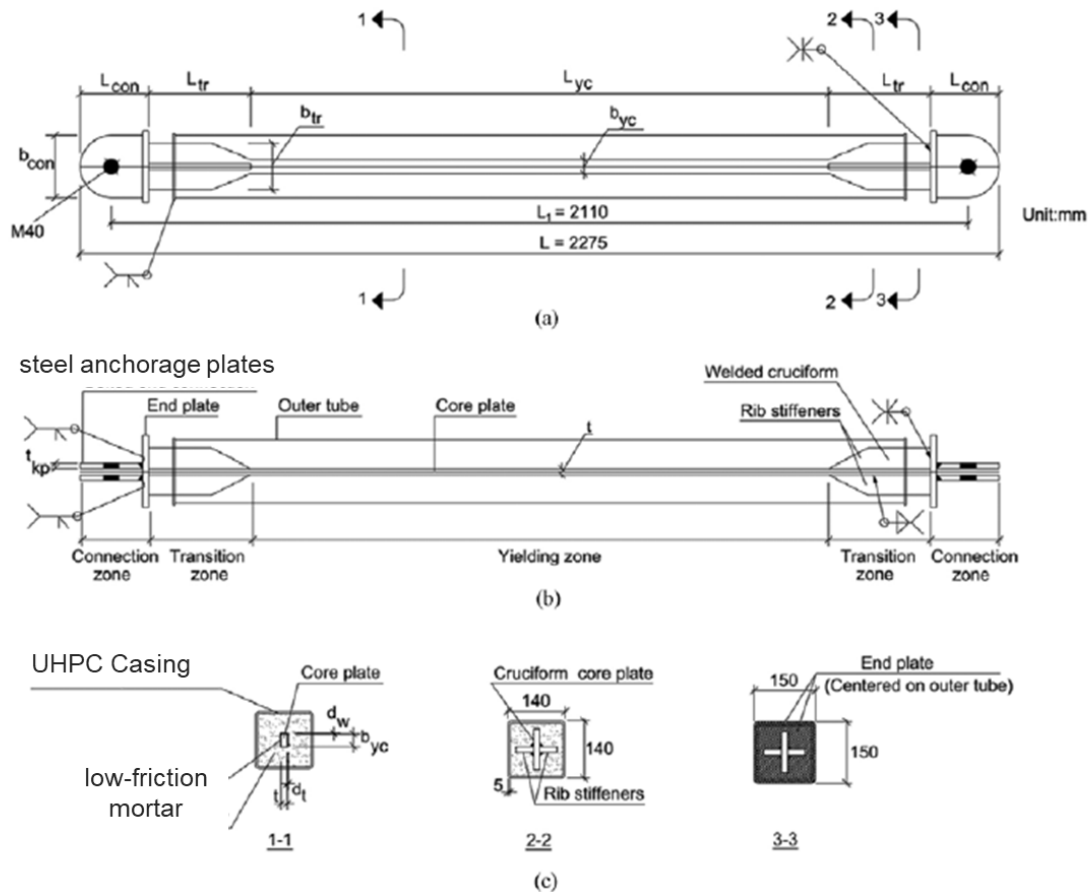


Fig 5.40 Detailed Components and Configuration of Buckling-Restrained Brace (BRB) with UHPC Casing

Table 5.32 Geometric Parameters of BRB with UHPC Casing.

Parameter	Value (mm)	Description
Yielding Zone Length (L_{ye})	1,410	Length of core designed to yield
Yielding Zone Width (b_{ye})	30	Core width in yielding zone
Core Thickness (t)	15	Thickness of steel core
Total Length (L)	2,275	Full length of BRB
Transition Zone Length (L_{tr})	249	Non-yielding transition zone

Modeling BRBs in ETABS

The BRB with UHPC casing is modeled using a multi-linear plastic link in ETABS to replicate its stable hysteresis behavior under cyclic loading. The steel core's yielding and hardening properties (e.g., yield strength = 257 MPa, ultimate strain = 38%) are defined in the plastic link, capturing energy dissipation through axial plasticity (Fig. 5.40). The UHPC casing's buckling-restraint effect is implicitly incorporated by adjusting the link's compressive stiffness modifier and strength enhancement factor to reflect the composite interaction between the steel core and UHPC. Parameters like unloading stiffness and residual strain (ϵ_r) are calibrated to

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experimental cyclic data to accurately represent the BRB’s post-yield behavior and minimal residual deformations. This approach efficiently simulates the UHPC casing’s role in stabilizing the steel core while maintaining computational simplicity for seismic analysis.

3.2.2.2.2. Strategy for Applying the Rehabilitation Technique

The Buckling-Restrained Braces (BRBs) with Ultra-High-Performance Concrete (UHPC) casing will be implemented throughout the building to address its seismic vulnerabilities. The BRBs will enhance the building's lateral stiffness and ductility, while the UHPC casing will provide additional confinement and prevent buckling under compressive forces. The braces will be installed diagonally across bays at critical levels, such as lower and mid-height stories, where excessive inter-story drift and brittle failure mechanisms have been identified. The UHPC casing will reinforce beam-column joints to improve their shear capacity and durability, ensuring the building complies with the seismic code (RPA 99/2003).

Table 5.33 Seismic Rehabilitation Strategy and Vulnerabilities Addressed by BRBs with UHPC Casing.

Direction	Technique	Vulnerabilities Addressed
X-Direction	X-Brace with Buckling-Restrained Braces (BRBs) and Ultra-High-Performance Concrete (UHPC) Casing	Reduces soft-story effects, improves lateral stiffness, and mitigates excessive inter-story drift. Prevents brittle failure in base columns and beam-column joints by redistributing seismic forces.
Y-Direction	Diagonal Buckling-Restrained Braces (BRBs) with Ultra-High-Performance Concrete (UHPC) Casing	Addresses localized vulnerabilities in base columns and beam-column joints, improves ductility, and ensures uniform lateral stiffness to mitigate localized damage.

3.3. Seismic Analysis Methodology

This section outlines the seismic analyses performed to evaluate the building following its retrofitting with BRBs equipped with UHPC casing. The analysis involves Pushover Analysis and Nonlinear Time History Analysis (NTHA), both conducted using ETABS to assess the building's static and dynamic seismic performance post-retrofitting.

For detailed parameters and methodologies used in these analyses, please refer to **Table 5.16** ("*Summary of Seismic Performance Evaluation Methods for Block I*"), as the same methods were applied to this case with adjustments for specific design conditions in the residential building.

3.3.1. Seismic Performance Results and Evaluation of the Retrofitted Building

3.1.3.1.1. Pushover Analysis Results

A. Base Shear vs. Roof Displacement Curve:

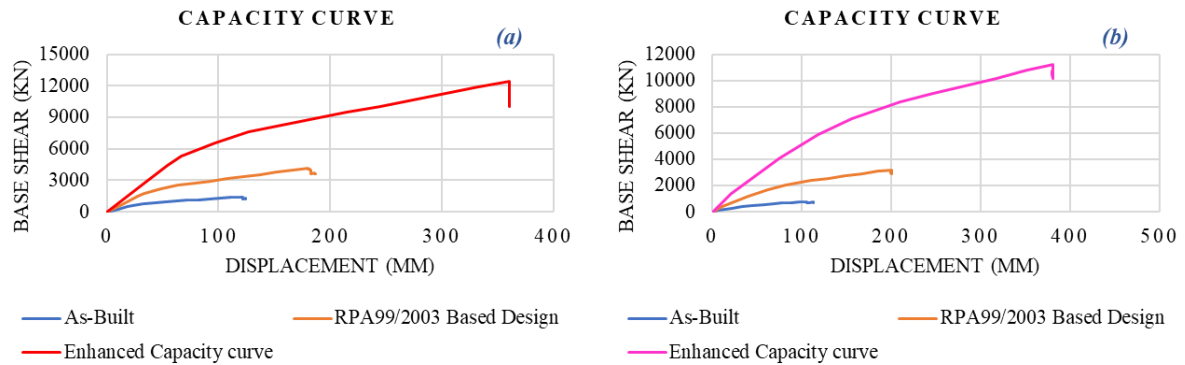


Fig. 5.41 Capacity Curves Comparison X and Y Directions.

B. Plastic Hinge Formation

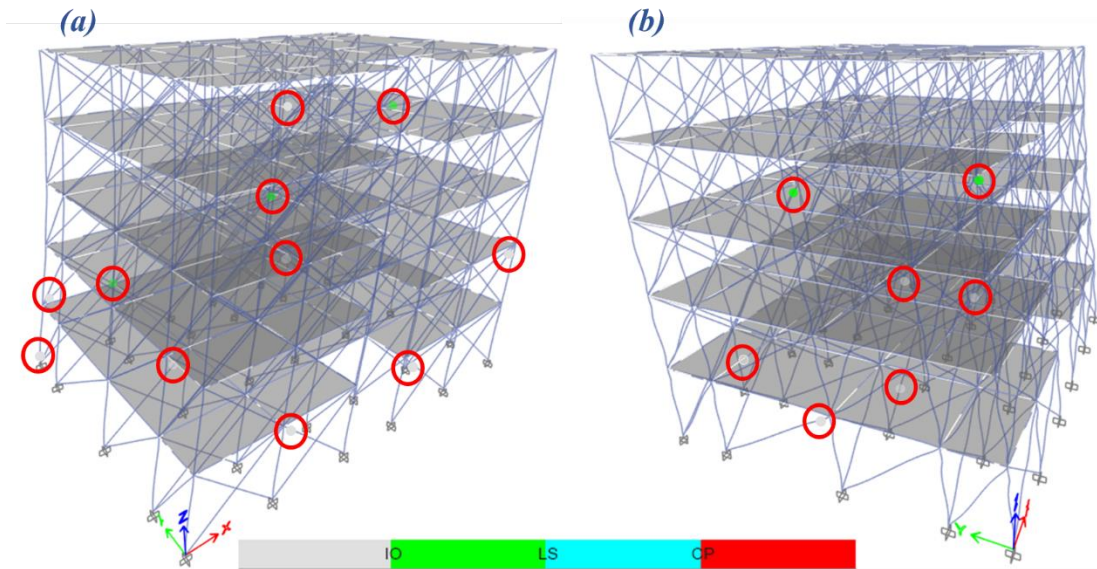
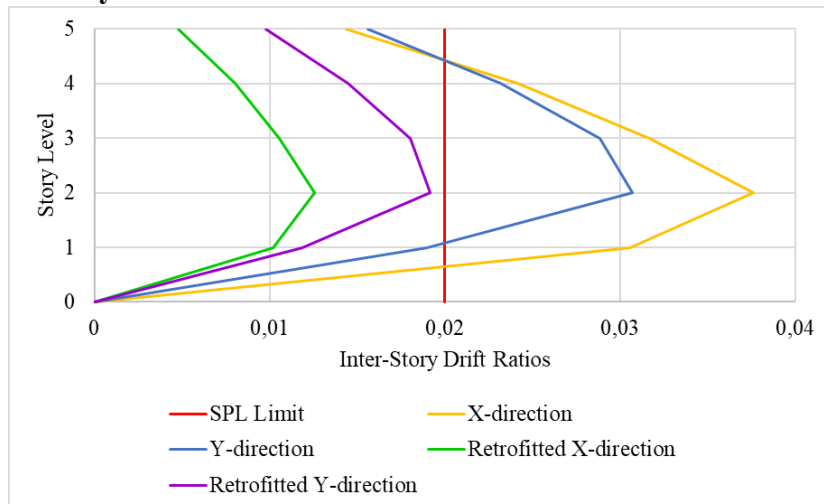


Fig. 5.42 Plastic Hinge Distribution in Retrofitted building: X-Direction (a) vs. Y-Direction (b).

C. Inter-Story Drift Ratios



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Fig. 5.43 Inter-Story Drift Ratios for: Un-Retrofitted vs. Retrofitted Performance in X and Y Directions.

D. Seismic Capacity vs. Demand Comparison

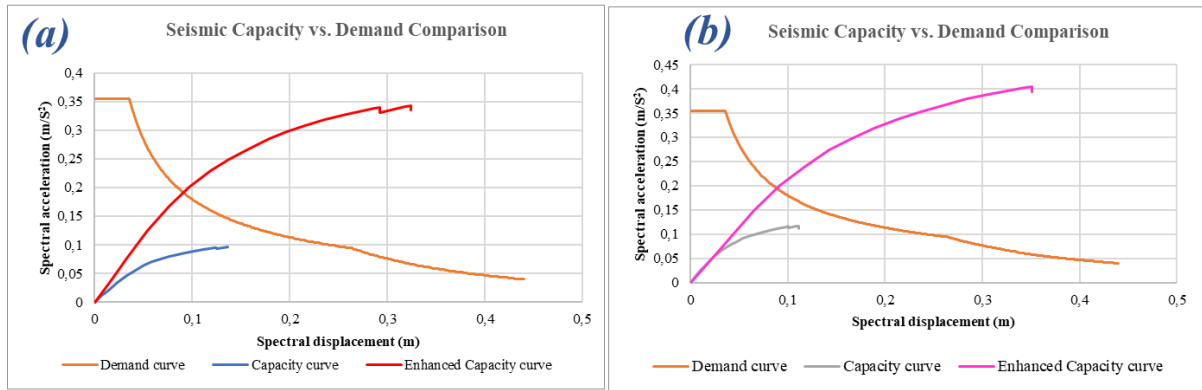


Fig. 5.44 Seismic Capacity and Enhanced Capacity vs. Demand Comparison for: X-Direction (a) vs. Y-Direction (b).

3.4.1.3. Nonlinear Time History Analysis (NTHA) Results

A. Residual displacement

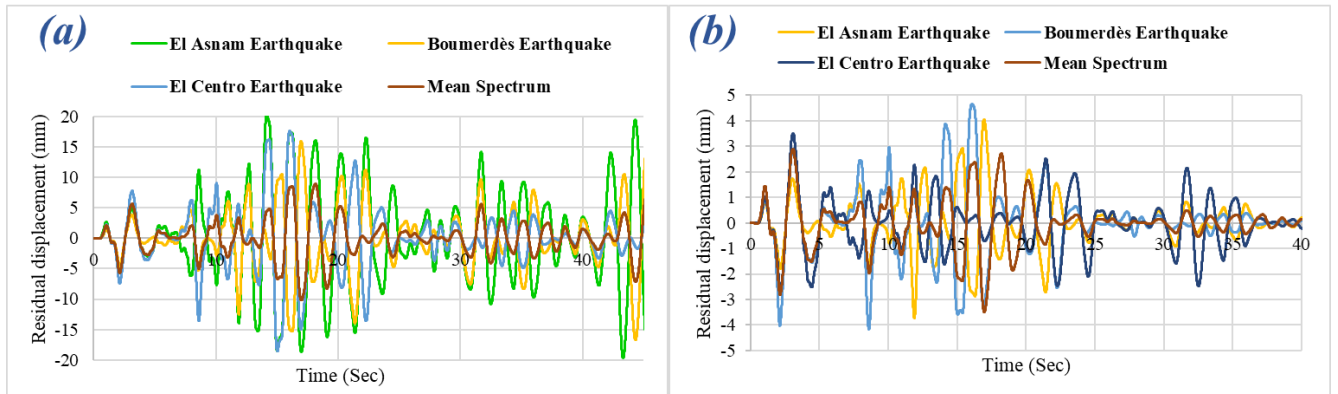


Fig. 5.45 Residual Displacement Time Histories for the building in the X-Direction: (a) Un-Retrofitted vs. (b) Retrofitted.

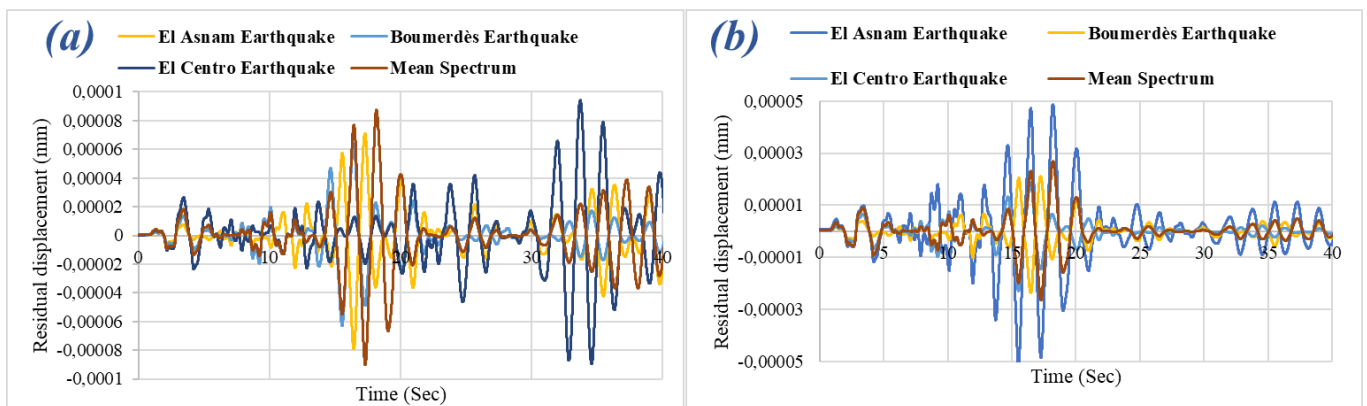


Fig. 5.46 Residual Displacement Time Histories for the building in the Y-Direction: (a) Un-Retrofitted vs. (b) Retrofitted.

B. Peak floor acceleration

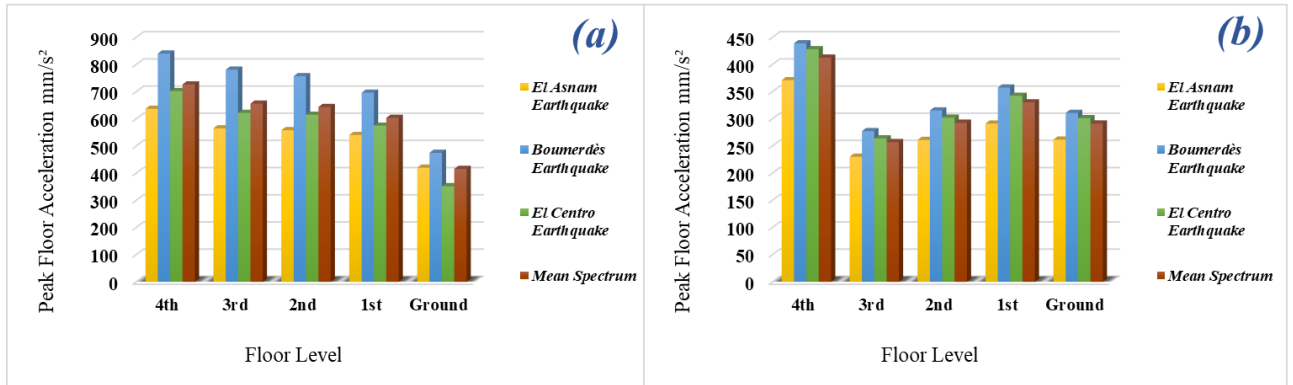


Fig. 5.47 Peak Floor Acceleration (PFA) for the building: (a) Un-Retrofitted vs. (b) Retrofitted in X Directions.

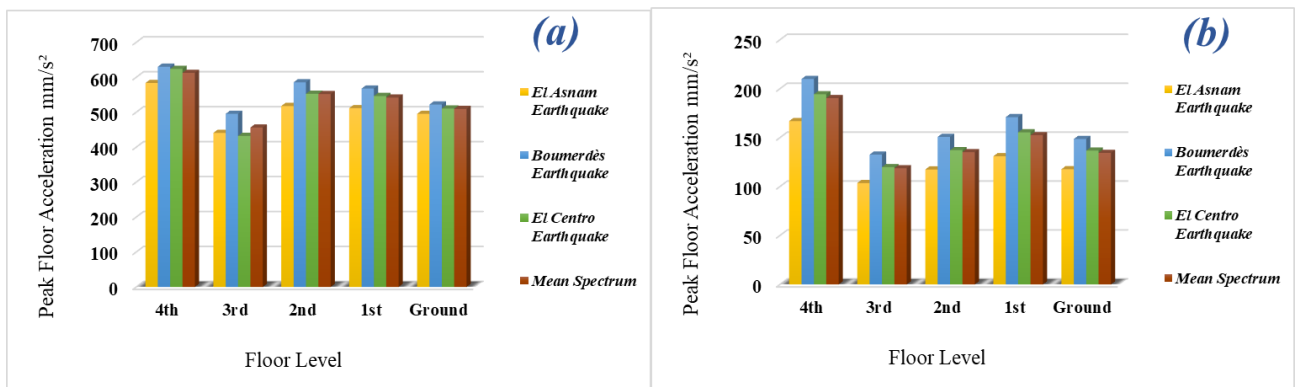


Fig. 5.48 Peak Floor Acceleration (PFA) for the building: (a) Un-Retrofitted vs. (b) Retrofitted in Y Directions.

C. Displacement Profiles

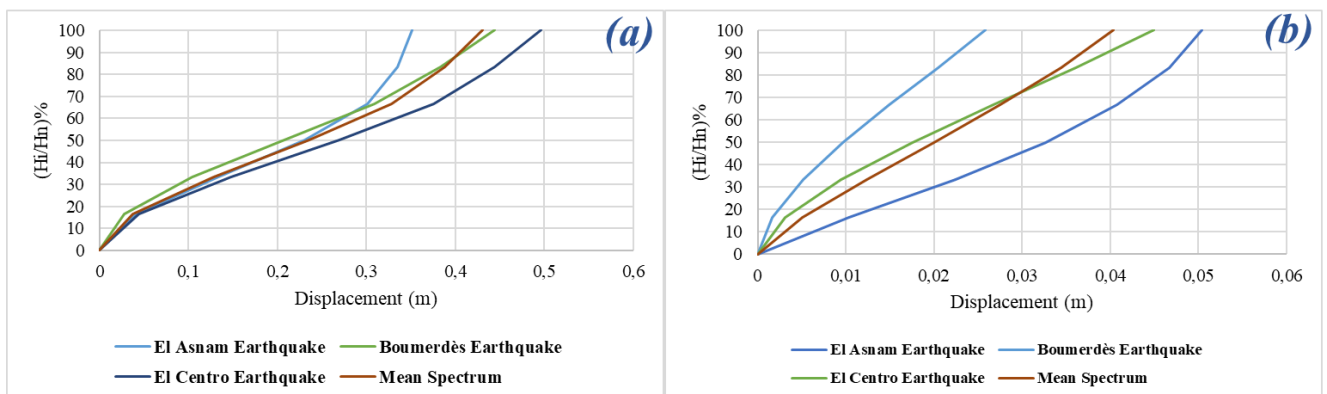


Fig. 49 .Displacement Profiles for the building: (a) Un-Retrofitted vs. (b) Retrofitted Under Seismic Loading

The retrofitted building using Buckling-Restrained Braces (BRBs) with UHPC casing demonstrates significant improvements in seismic performance across multiple metrics. The capacity curves indicate a dramatic enhancement in base shear capacity, with the retrofitted structure in the X-direction reaching approximately 12,000 kN, compared to the un-retrofitted base shear of just 1,500 kN, reflecting a 3-4x increase in lateral force resistance. Similar results are observed in the Y-direction, where the base shear capacity also increased significantly,

showcasing the effectiveness of the retrofitting strategy. Plastic hinge distribution reveals that most hinges are concentrated in the BRBs, ensuring controlled energy dissipation and minimal damage to critical structural components like columns and beams. Most hinges remain within the Immediate Occupancy (IO) and Life Safety (LS) performance levels, indicating the structure's resilience under seismic loading. The inter-story drift ratios for the retrofitted structure are well within acceptable limits ($<2\%$), with the X-direction drifts reduced from over 5% to $\sim 1.5\%$ and the Y-direction drifts reduced to $\sim 1.0\%$, highlighting the retrofitting's ability to control lateral displacements.

In terms of seismic demand, the retrofitted structure exceeds the expected requirements, as shown by the capacity vs. demand comparison, ensuring compliance with modern seismic codes (e.g., RPA99/2003). Results from the nonlinear time history analysis (NTHA) confirm the retrofitting's effectiveness in reducing residual displacements and peak floor accelerations. Residual displacements are significantly reduced—less than 5 mm in both directions compared to over 15 mm in the unretrofitted state—indicating improved structural recovery after seismic events. Peak floor accelerations are also reduced by 20-30%, particularly in the upper stories, minimizing non-structural damage and enhancing occupant safety. Collectively, these results demonstrate that the retrofitting strategy using BRBs with UHPC casing has effectively addressed the building's pre-existing vulnerabilities, transforming it into a seismically resilient structure capable of withstanding significant lateral forces while maintaining functionality and safety during and after seismic events. This robust retrofitting solution ensures long-term protection against future seismic hazards.

Step 04: Post-Rehabilitation Validation

Following the steps of the Algeria-Specific Seismic Assessment Framework, the Post-Rehabilitation Validation phase evaluates the effectiveness of the retrofitting measures implemented on the Case 2 building. This crucial step ensures that the rehabilitated structure meets the targeted seismic performance benchmarks, such as Immediate Occupancy (IO) or Life Safety (LS), while addressing the vulnerabilities identified in the as-built condition. Using advanced analytical techniques and comparative studies, the seismic performance of the retrofitted structure is rigorously assessed to confirm alignment with theoretical predictions and practical objectives.

4.1. Results for Case Study 02

The post-rehabilitation validation demonstrates a substantial improvement in the seismic behavior of the Case 2 building. The results highlight the effectiveness of the retrofitting

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strategy using Buckling-Restrained Braces (BRBs) with UHPC casing, which directly addressed the vulnerabilities identified during the assessment phase:

4. The retrofitted building achieved the Life Safety (LS) performance level, ensuring the structure remains safe, functional, and operational immediately after a seismic event.
5. No significant repairs are required post-earthquake, validating the robustness of the applied retrofitting measures.
6. Post-rehabilitation pushover analysis confirms that plastic hinges are predominantly concentrated in the BRBs, particularly in the lower and mid-height levels where seismic demands are highest.
7. Critical structural elements, such as columns and beam-column joints, remain largely undamaged, with no hinge formations exceeding Life Safety (LS) thresholds. This demonstrates the success of the retrofitting strategy in redistributing seismic forces and protecting the primary structural frame.
8. The inter-story drift ratios were significantly reduced:
 - In the X-direction, drifts decreased from over 5% in the un-retrofitted structure to below 1.5%.
 - In the Y-direction, drifts were reduced to less than 1.0%, ensuring compliance with the RPA 99/2003 code requirements.
 - These reductions confirm the retrofitting system's ability to effectively control lateral displacements, preventing story collapse and ensuring structural stability.
9. Residual displacements from Nonlinear Time History Analysis (NTHA) were reduced to less than 5 mm in both directions, compared to over 15 mm in the as-built structure. This demonstrates improved energy dissipation and recovery, with minimal permanent deformation after seismic events.
10. The BRBs successfully absorbed seismic energy, limiting the demand on other structural components. The improved hysteretic response, with no signs of stiffness degradation, validates the enhanced ductility of the retrofitted structure.
11. The performance of the retrofitted Case 02 building aligns well with the findings of experimental and numerical studies on BRBs and UHPC materials:
 - **Enhanced Ductility:** Studies by Wu et al. [84] and Yang et al. [86] on BRBs with advanced casings validate their effectiveness in resisting cyclic loading and dissipating energy, observations that match the hysteretic behavior of Case 02 building.

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- **Improved Confinement:** UHPC's crack resistance and compressive strength ensured the structural stability of the BRBs under high strains, as evidenced by the reduced drift and hinge formation.
- **Global Stability:** Eliminating soft-story behavior and concentrated failure mechanisms aligns with practical case studies on retrofitted buildings in seismic zones.

Step 05: Decision-Making and Final Evaluation

The post-rehabilitation evaluation synthesizes all analytical and observational results to classify the seismic performance of the Case 02 building. Based on these findings:

Seismic Performance Classification:

- The retrofitted structure achieves the Life Safety (LS) classification, ensuring functionality, safety, and compliance with modern seismic codes.
- The significant reductions in inter-story drifts, controlled hinge formation, and negligible residual displacements support this classification.

5.1. Key Indicators of Performance:

- **Plastic Hinge Distribution:** Hinges are limited to BRBs, with no critical damage to columns or joints.
- **Drift Control:** All inter-story drift ratios remain below 2%, complying with RPA 99/2003 limits.
- **Base Shear Capacity:** The building achieves a 3-4x increase in base shear resistance, ensuring superior resilience to seismic forces.
- **Residual Displacement:** Negligible permanent deformations validate the retrofitting system's energy dissipation and recovery capabilities.

5.2. Recommendations for Ongoing Monitoring and Maintenance:

- **Routine Inspections:** Periodic inspections of the BRBs and UHPC casings to ensure their continued performance.
- **Structural Health Monitoring (SHM):** Implementing real-time SHM systems to track strain and displacement in critical components.
- **Post-Seismic Inspections:** Immediate evaluations after seismic events to confirm that the structure remains in the LS category.

5.3.2.3 Case Study 3: Hypothetical Case Study: Seismic Resilience Assessment of Irregular RC Buildings with Brace Variations (Based on BAKHOUCHE et al. [48])

Introduction:

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This case study applies the Algeria-Specific Seismic Assessment Framework (developed in Chapter 3) to evaluate the seismic resilience of a hypothetical L-shaped reinforced concrete (RC) building. The L-section was selected for this study due to its common use in urban designs where space constraints make irregular shapes advantageous for both aesthetics and functionality. However, the inherent irregularity of the L-section introduces complexity in its seismic behavior, particularly under lateral forces during earthquakes.

The paper by BAKHOUCHE et al. [48] Analyzed four different building configurations—I, L, plus, and T-shaped—focusing on their seismic response to varying brace placements. While all four configurations present valuable insights, the L-section was chosen for this case study due to its specific challenges in load distribution and lateral force resistance. As demonstrated in the paper, the L-shaped structure's irregular plan leads to more complex seismic behavior, making it an ideal candidate for applying the Algeria-Specific Seismic Assessment Framework and testing the effectiveness of various X-brace configurations.

Step 01: Data Collection

A. Building Geometry and Layout

Table 5.34. Building Geometry and Layout.

Parameter	Description
Building Shape	L-shaped
Number of Floors	12 floors with a total height of 36.72 meters (average floor height of 3.06 meters).
Irregularities	L-shaped plan with irregularity due to non-rectangular geometry.
Floor Plan	Each span is 5 meters wide in both x and y directions, with a 200 mm slab thickness, and is considered a rigid diaphragm.

Table 5.35 Material Properties of Concrete and Steel for Seismic Assessment.

Material properties	Concrete	Grade	C25/30
		Modulus of elasticity	31000 MPa
		Poisson ratio	0.2
		Density	2500 Kg/m ³
	Steel reinforcement	Grade	S235
		Modulus of elasticity	210000 MPa
		Minimum yield stress	235 MPa
		Minimum tensile strength	360 MPa
		Poisson ratio	0.3
		Density	7850 Kg/m ³

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Table 5.36 Dimensions and Specifications of Structural Elements

Structural Element	Description
Foundation Type	Shallow isolated footings
Soil Classification	S1 (Rocky Soil) as per RPA 99/2003
Shear Wave Velocity (V_s)	≥ 800 m/s
Beam and Column Dimensions	Columns: 45x45 cm; Beams: 35x35 cm.
Slab Thickness	200 mm, considered as a Solid Slab
Load Distribution	Moment-resisting frame (SMRF) is assumed to be the primary system for lateral load resistance.

Table 5.37. Seismic Zone, Building Function, and Design Standards.

Parameter	Description
Seismic Zone	Seismic Zone III (high seismic activity in Algeria).
Peak Ground Acceleration (PGA)	0.35g
Building Function	Residential
Design Standards Applied	RPA99/2003 (Algerian seismic standard) for seismic design, Eurocode 2 for concrete design.

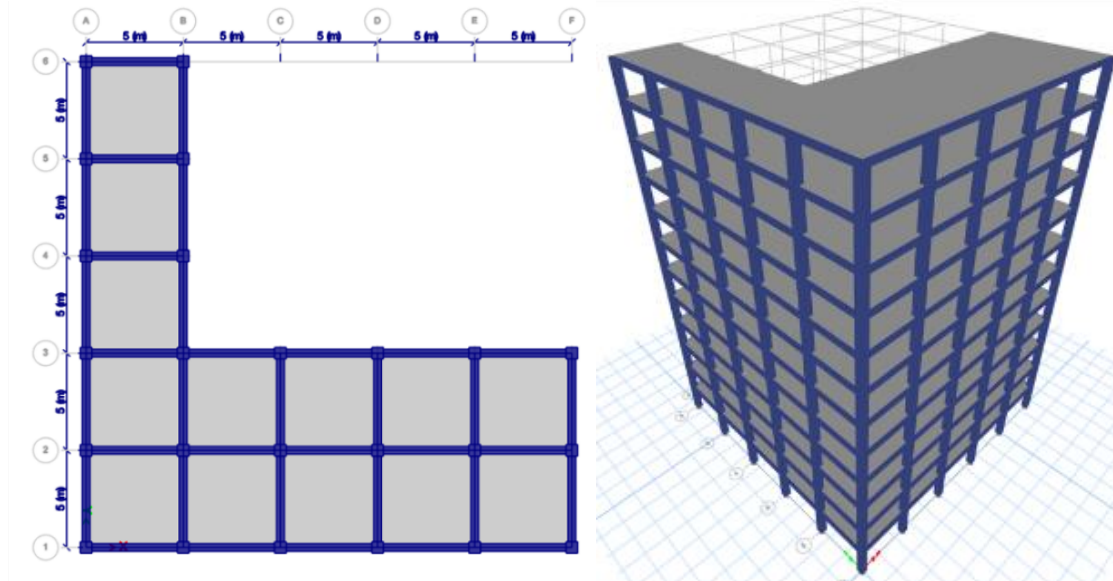


Fig 5.50 Plan and 3D View of a 12-Story Irregular RC Building.

Table 5.38. Reinforcement Details for Columns and Beams.

Element	Level	Reinforcement Details
Columns	Ground Floor	Longitudinal Bars: 6 $\varnothing 14$ mm Stirrups: $\varnothing 8$ mm @ 300 mm spacing
	1st–3rd Floors	Longitudinal Bars: 4 $\varnothing 14$ mm

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		Stirrups: Ø8 mm @ 250 mm spacing
	4th–6th Floors	Longitudinal Bars: 4 Ø12mm
		Stirrups: Ø8 mm @ 250 mm spacing
	7th–9th Floors	Longitudinal Bars: 4 Ø12mm
		Stirrups: Ø8mm @ 200 mm spacing
	10th-12th floors	Longitudinal Bars: 4 Ø10mm
		Stirrups: Ø6 mm @ 200 mm spacing
Beams	All Levels	Top/Bottom Reinforcement: 2 Ø12 mm (top), 2 Ø14 mm (bottom)
		Stirrups: Ø6 mm @ 200 mm spacing

B. Seismic Performance Evaluation

Table 5.39. Proposed Seismic Performance Levels (SPLs) for the L-Shaped Structure.

Performance Level	Objective	Indicators
Life Safety (LS)	The building should ensure safety for occupants during and immediately after an earthquake, providing structural integrity and safe evacuation. Although some structural damage may occur, the building should not collapse.	<ul style="list-style-type: none"> - No significant damage to primary load-bearing elements (e.g., columns, beams, foundation). - Some non-structural elements (e.g., partitions, windows) may suffer damage, but the building remains safe and operational for evacuation.

Step 02: Structural Analysis Methods (Pre-Rehabilitation)

For the seismic performance evaluation of the L-shaped residential building in Case Study 03, pushover analysis was chosen as the primary method of structural analysis. This approach is particularly suitable for assessing the seismic behavior of irregularly shaped buildings, which require a deeper understanding of their nonlinear performance due to plan irregularities.

- Pushover analysis effectively captures the structure's nonlinear behavior, which is essential when evaluating the seismic performance of irregular buildings. As noted in RPA99/2003, L-shaped buildings are prone to increased torsional effects and stress concentrations due to their irregular geometry, making nonlinear analysis indispensable for identifying vulnerabilities.
- Buildings with irregular plans, such as the L-section, experience uneven distribution of seismic forces, often leading to torsion and localized failures in specific areas. RPA99/2003

highlights that irregular buildings require stricter detailing and design provisions to mitigate these vulnerabilities. Pushover analysis helps pinpoint these weak zones, such as:

- Beam-column joints, which are critical load transfer points.
 - Peripheral columns in the L's longer arms, which may experience higher shear and moment demands.
 - Torsional effects, which can cause excessive displacement at corners and lead to uneven stress distribution.
- Unlike linear static analysis, pushover analysis accounts for inelastic deformations in structural elements, reflecting how the building behaves under increasing seismic loads. This is critical for assessing the performance of irregularly shaped buildings, where plastic hinges may form due to uneven force distribution.

Pushover analysis generates critical outputs for evaluating the building's performance and planning rehabilitation, including:

- Force-displacement curves, which help assess whether the building can achieve the target Seismic Performance Level (SPL), such as Life Safety (LS).
- Vulnerability assessment, identifying weaknesses in the structure caused by the L-shaped irregularity, including high stress at corners and torsional effects.
- Capacity-demand comparison, determining if the building's structural capacity is sufficient to resist seismic forces outlined in RPA99/2003.
- Rehabilitation planning, guiding retrofiting strategies to improve the seismic resilience of the building.

2.1. Results from Pushover Curves

A. Capacity Curve:

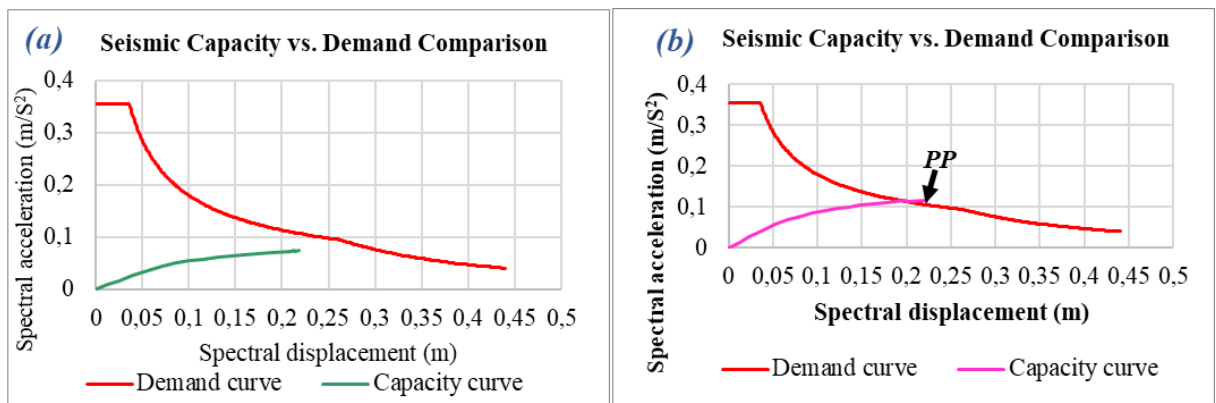


Fig 5.51. Seismic Capacity vs. Demand Comparison for: X-Direction (a) vs. Y-Direction (b).

B. Plastic Hinge Distribution:

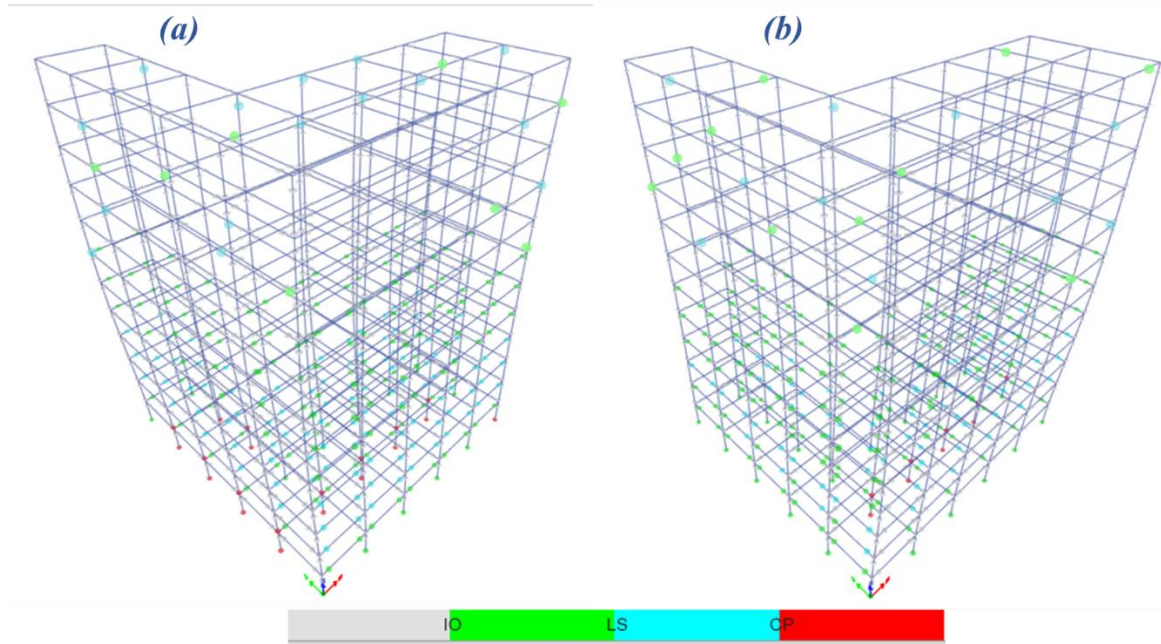


Fig 5.52 Plastic Hinge Distribution: X-Direction (a) vs. Y-Direction (b).

C. Inter-Story Drift Ratios

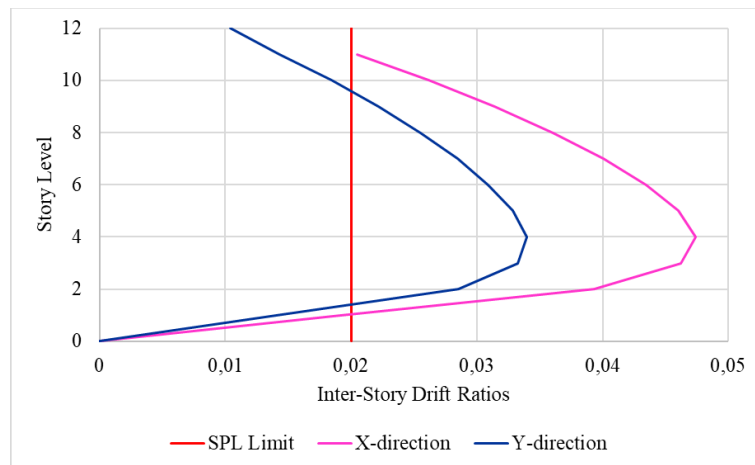


Fig 5.53. Inter-Story Drift Ratio Curves.

D. Torsional Irregularity Ratio (η_t)

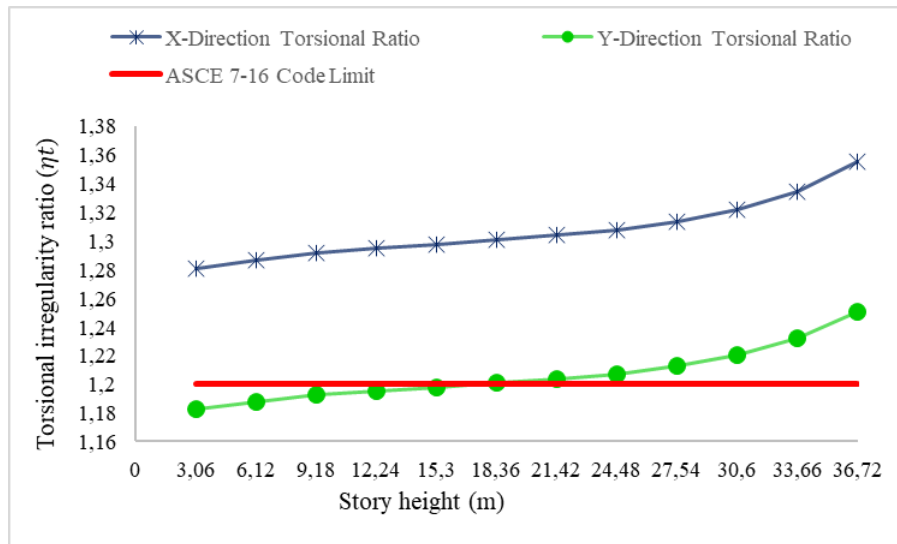


Fig 5.54. Torsional Irregularity Ratios Across Story Height.

E. Ductility Ratio (μ):

Table 5.40. Ductility Ratios for X and Y Directions.

Direction	Yield Displacement (Δ_{yield} , cm)	Ultimate Displacement ($\Delta_{ultimate}$, cm)	Ductility Ratio ($\mu = \Delta_{ultimate}/\Delta_{yield}$)	RPA99/2003 Code Limit ($\mu \geq 5$)
X-Direction	7,8	22,3	2.86	5,0
Y-Direction	12,9	53,1	4,12	5,0

The seismic performance evaluation of the L-shaped reinforced concrete (RC) structure highlights several critical vulnerabilities and deficiencies that must be addressed. The seismic capacity vs. demand comparison revealed that the X-direction is unable to meet seismic demand, with the capacity curve failing to intersect the demand curve sufficiently. This demonstrates a lack of lateral strength in the X-direction, particularly in the more extended arm of the L-shape, which is heavily impacted by torsional amplification. In contrast, the Y-direction showed better alignment between capacity and demand, reflecting comparatively stronger lateral performance, though reserve capacity remains limited.

The plastic hinge distribution further emphasizes structural imbalances. In the lower stories, the X-direction exhibits significant hinges transitioning into Collapse Prevention (CP) (red), indicating critical stress concentrations and potential failure points. Meanwhile, the Y-direction primarily shows Life Safety (LS) (blue) hinges in the lower stories, reflecting better-controlled inelastic behavior. However, the upper stories in both directions remain dominated by elastic (green) hinges, suggesting that these levels are underutilized in energy dissipation and fail to transition into the inelastic range, leaving the lower stories to bear the majority of seismic stress.

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The inter-story drift ratios confirm these findings, with the X-direction exceeding allowable drift limits, especially in the middle and upper stories, reflecting excessive lateral deformation. This aligns with the structure's low ductility ratio and insufficient hinge formation in the X-direction. Conversely, the Y-direction remains within acceptable drift limits for most of the structure, with minor exceedances in the upper stories, signaling a better, though not optimal, performance.

The torsional irregularity ratio (ηt) results expose a key vulnerability in the X-direction, where values exceed the code limit of 1.2 throughout the structure's height. This indicates severe torsional effects driven by the asymmetry of the L-shaped plan, leading to uneven force distribution and elevated stress on critical elements. The Y-direction demonstrates more stable performance, with ηt remaining within limits for most stories, though minor irregularities in the upper stories require attention. Finally, the ductility ratio (μ) results underscore the structure's inability to dissipate seismic energy effectively. The X-direction's ductility ratio of 2.86 is significantly below the code requirement of $\mu \geq 5$, indicating insufficient inelastic deformation capacity and a high risk of brittle failure. While the Y-direction performs better, achieving a ductility ratio of 4.12, it still falls short of the required threshold, further reinforcing the need for retrofitting.

In summary, the L-shaped RC structure suffers from significant seismic vulnerabilities. The X-direction exhibits insufficient ductility, severe torsional irregularity, and excessive deformation, particularly in the lower and middle stories. The Y-direction performs comparatively better but still requires improvements to meet seismic design standards. The hinge distribution highlights a reliance on the lower stories for energy dissipation, leaving the upper stories underutilized and vulnerable. Targeted retrofitting measures, including strengthening beam-column joints, introducing lateral brace, and redistributing stiffness, are essential to improve the structure's seismic resilience and bring it into compliance with RPA99/2003 standards.

2.2. Vulnerability Assessment

Table 5. 41. Summary of Structural Vulnerabilities in the L-Shaped RC Building.

Vulnerability	Description	Impact
Torsional Irregularity (X-Direction)	Severe torsional effects due to the asymmetry of the L-shaped plan lead to a high torsional irregularity ratio ($\eta t > 1.2$) throughout the structure.	Uneven force distribution and stress concentration, particularly in lower stories.
Inadequate Ductility (X-Direction)	Low ductility ratio ($\mu = 2.86$) in the X-direction, significantly below the RPA99/2003 code limit ($\mu \geq 5$).	Insufficient inelastic deformation capacity, leading to brittle failure and poor energy dissipation.

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Plastic Distribution Direction)	Hinge (X-	Limited plastic hinge formation in upper stories, dominated by elastic hinges.	Over-reliance on lower stories for energy dissipation, with upper stories underutilized in seismic performance.
Excessive Story Drifts Direction)	Inter- (X-	Drift ratios exceed allowable limits, particularly in upper stories.	High lateral deformations that can compromise structural integrity and non-structural elements.
Insufficient Ductility (Y-Direction)		Ductility ratio ($\mu = 4.12$) is below the required threshold ($\mu \geq 5$).	While better than the X-direction, still limits energy dissipation and inelastic deformation in the upper stories.
Plastic Distribution Direction)	Hinge (Y-	Plastic hinges concentrated in the lower stories, with upper stories primarily showing elastic behavior.	Lower stories bear most of the seismic demand, while upper stories are underutilized for energy dissipation.
Imbalance in Energy Dissipation		Lower stories dominate in energy dissipation, while upper stories remain primarily elastic.	Potential for failure in lower stories due to high energy concentrations; upper stories do not contribute sufficiently to energy dissipation.
Vulnerability to Brittle Failure Direction)	to (X-	Lack of sufficient inelastic behavior in the X-direction leads to potential for brittle failure.	Reduced resilience under significant seismic events, increasing the risk of sudden failure.

Step 03: Rehabilitation Strategy Design

Following the evaluation in Step 01: Data Collection and Step 02: Seismic Performance Evaluation, the L-shaped reinforced concrete (RC) building has been identified to possess significant structural deficiencies when subjected to seismic forces. Key issues include inadequate lateral resistance in the X-direction, limited inelastic deformation capacity, and torsional irregularities, all increasing the building's vulnerability to seismic events. The proposed rehabilitation strategy addresses these deficiencies through advanced retrofitting measures to improve seismic resilience, ensure compliance with RPA99/2003, and enhance the structure's overall performance.

3.1. Damage Classification

Table 5.42. Damage Classification for the L-Shaped Residential Building (Case Study 3).

Direction	Damage Classification	Severity	Reason	Structural	Failure
				Elements Affected	Mechanisms
X-Dir	Severe Damage	Critical	The structure fails to meet seismic demands due to insufficient base shear capacity,	Base columns, beam-column joints, upper-story columns	- Progressive hinge formation at critical locations

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			excessive lateral flexibility, torsional irregularity, and localized failure points. Plastic hinges predominantly form in critical areas, increasing the risk of progressive collapse.		- Excessive lateral displacements leading to structural instability - Inadequate column reinforcement and insufficient confinement
Y-Dir	Moderate Damage	Moderate	The Y-direction performs better than the X-direction with improved base shear capacity and reduced lateral displacements. However, localized plastic hinge formation in base columns and joints, particularly in the lower stories, still indicates weaknesses.	Base columns, beam-column joints	- Localized hinge formation - Insufficient confinement in critical joints and columns

Conclusion

The L-shaped RC building demonstrates significant seismic vulnerabilities in both the X and Y directions. Specifically:

- Severe Damage in the X-direction, attributed to torsional irregularities, plastic hinge formation, and excessive inter-story drifts, requires immediate strengthening measures to ensure the building can withstand seismic loads.
- Moderate Damage in the Y-direction, with localized weaknesses in the base columns and beam-column joints, necessitates focused retrofitting to enhance the building's lateral resistance and energy dissipation capacity.

3.2. Seismic Rehabilitation of L-Shaped RC Structure Using Steel X-Brace for Enhanced Lateral Resistance

Steel brace, particularly in the X-brace configuration, has proven to be one of the most effective methods for enhancing the lateral resistance of irregularly shaped structures. Recent studies have demonstrated that X-brace significantly improves seismic performance by providing efficient energy dissipation and reducing torsional irregularities. For instance, Bakhouché et al. [48] investigated the nonlinear behavior of irregular RC buildings with varying X-brace positions, concluding that optimal placement (e.g., at re-entrant corners or along longer spans) reduces inter-story drift by up to 40% and mitigates stress concentrations in L-shaped layouts [1]. This configuration optimizes structural stiffness and load distribution, addressing critical vulnerabilities such as excessive lateral displacements and localized hinge formations. The use of steel X-brace not only ensures compliance with modern seismic design standards but also enhances the overall resilience of the building, making it an ideal solution for the rehabilitation of L-shaped RC structures [92] [93] [94].

3.2.1. Objectives of Rehabilitation

X-Direction:

- Improve lateral stiffness to reduce torsional irregularities.
- Increase base shear capacity to meet seismic demand.
- Address plastic hinge formation in critical areas such as base columns and beam-column joints.
- Reduce excessive inter-story drifts by enhancing the overall lateral resistance.
- Ensure uniform energy dissipation through improved damping systems.

Y-Direction:

- Strengthen base columns and beam-column joints to prevent localized hinge formation.
- Increase lateral resistance by adding X-brace to distribute forces evenly.
- Enhance reinforcement and confined detailing in critical elements.
- Ensure the Y-direction's ductility and energy dissipation capacity to meet seismic performance standards.

3.2.2. Modeling Steel Braces in ETABS

3.2.2.1. Material Properties of Steel Braces

Steel X-brace will be used to enhance the structure's lateral resistance to rehabilitate the L-shaped RC building. The material properties of the steel braces are essential for ensuring that they can effectively resist seismic forces and contribute to energy dissipation. The material specifications for the steel braces are as follows:

Table 5.43. Material Properties of S235 Steel (Eurocode 3: EN1993-1-1).

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Property	Value
Steel Grade	S235
Modulus of Elasticity (E)	210,000 MPa
Poisson's Ratio (ν)	0.3
Yield Strength (f_y)	235 MPa
Tensile Strength (f_u)	360 MPa
Density (ρ)	7850 kg/m ³

These material properties ensure that the brace system is both strong and ductile, capable of absorbing seismic energy without significant plastic deformation, contributing to the building's overall seismic resilience.

Table 5.44. Geometry of Steel X-Brace (Eurocode 3: EN1993-1-1).

Parameter	Value
Cross-Section	(HSS) 200×200×12
Outer Dimensions (mm)	200 (width) × 200 (height)
Wall Thickness (t)	12 mm
Slenderness (c/t)	$(200-2 \times 12)/12=14,7$
Cross-Sectional Area (A) mm ²	9,024
Moment of Inertia (I) mm ⁴	72.8×10^6

Modeling Steel Braces in ETABS

In ETABS, steel braces are modeled as frame elements that are connected to the main structure at strategic points. The following steps will be followed for the modeling process:

- Steel X-brace will be modeled as diagonal braces placed in the X-pattern to resist lateral forces.
- Frame elements will be assigned to represent the brace, ensuring they can accurately capture axial and shear forces.
- The brace connection will be modeled as rigid or semi-rigid connections between the steel and concrete structures. The design will ensure that the brace can efficiently transfer axial forces, shear forces, and bending moments to the main structure.

3.2.2.2. Strategy for Applying Steel Braces in the Structure

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Based on the earlier results and the structural vulnerabilities identified, the X-brace system will be applied in both X and Y directions to enhance the building's seismic resilience. The locations and justification for applying the brace are outlined below:

- **X-Direction (Longer Arm of the L-Shape):**

Strategic Placement:

- X-brace will be applied in all stories of the X-direction, focusing on the central bays of the longer arm of the L-shape. These areas are particularly vulnerable due to significant torsional irregularities and excessive lateral displacements observed in the earlier analysis.
- Placing the brace in the central bays helps distribute lateral forces effectively, mainly where torsional effects and displacement issues were most pronounced. This strategic placement will mitigate the adverse effects of torsional instability and enhance lateral resistance across the entire building height.
- To ensure uniform energy dissipation, additional braces will be applied to the upper stories as well. This ensures that all stories participate in the energy dissipation process, preventing the over-reliance on lower stories and ensuring more balanced seismic behavior across the structure.

Justification:

- The base shear capacity in the X-direction was previously insufficient, and significant torsional effects were observed. By introducing X-brace in all stories, particularly in the critical central bays, we will significantly increase lateral stiffness, torsional stability, and load distribution across the building.
- The uniform placement of brace across all stories ensures that the entire structure is reinforced, improving overall structural behavior and allowing the building to better meet the seismic demands as per RPA99/2003.

- **Y-Direction (Shorter Arm of the L-Shape):**

Strategic Placement:

- X-brace will also be applied in all stories of the Y-direction, with braces placed in the interior bays of the shorter arm. While the Y-direction demonstrated better seismic performance compared to the X-direction, localized weaknesses were still observed in base columns and beam-column joints.
- Applying the brace in all stories of the Y-direction will reinforce the structure's overall lateral resistance and ensure uniform load distribution. This improves the capacity to

resist lateral forces, particularly in the lower stories, where the structure's performance was found to be weaker.

Justification:

- The Y-direction performed better in earlier analyses but still exhibited localized vulnerabilities, particularly in the lower stories. By applying X-brace throughout the entire height of the structure, we ensure that energy dissipation is uniformly distributed across all stories, improving the building's seismic resilience.
- The additional brace in the lower stories of the Y-direction will help distribute lateral forces more evenly, reducing the risks of failure due to localized hinge formation and improving overall seismic performance.

3.3. Seismic Analysis Methodology for Case Study 3: L-Shaped RC Building with X-Brace Retrofit

This section outlines the seismic analyses performed to evaluate the performance of the L-shaped reinforced concrete (RC) building after retrofitting with steel X-brace in both X and Y directions. The analysis includes Pushover Analysis and Nonlinear Time History Analysis (NTHA), both conducted using ETABS to assess the building's static and dynamic seismic performance post-retrofit.

- **Pushover Analysis:** The pushover analysis was performed to assess the seismic performance of the building after the installation of the BRBs with UHPC casing. This analysis critically evaluates the building's ability to resist lateral seismic forces and undergo controlled deformation under load. The parameters and configurations used in the pushover analysis are as follows:

Load Patterns:

Uniform Load Pattern: Lateral forces are distributed equally across all floors.

Modal Load Pattern: Lateral forces distributed according to the structure's fundamental vibration mode.

Plastic Hinge Assignments:

Hinges were assigned to:

Columns: Axial-flexural hinges (P-M2-M3) to account for combined axial and bending effects.

Beams: Flexural hinges (M3) to simulate bending failure.

Steel X-Braces: Axial-only hinges were assigned to the steel X-brace elements to capture their tension-compression behavior under cyclic loading. These hinges simulate the energy dissipation capacity of the brace system, which significantly enhances the structure's seismic performance.

Performance Levels:

The analysis evaluated Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) thresholds as per FEMA 356 guidelines.

3.3.1. Results of: Pushover Analysis

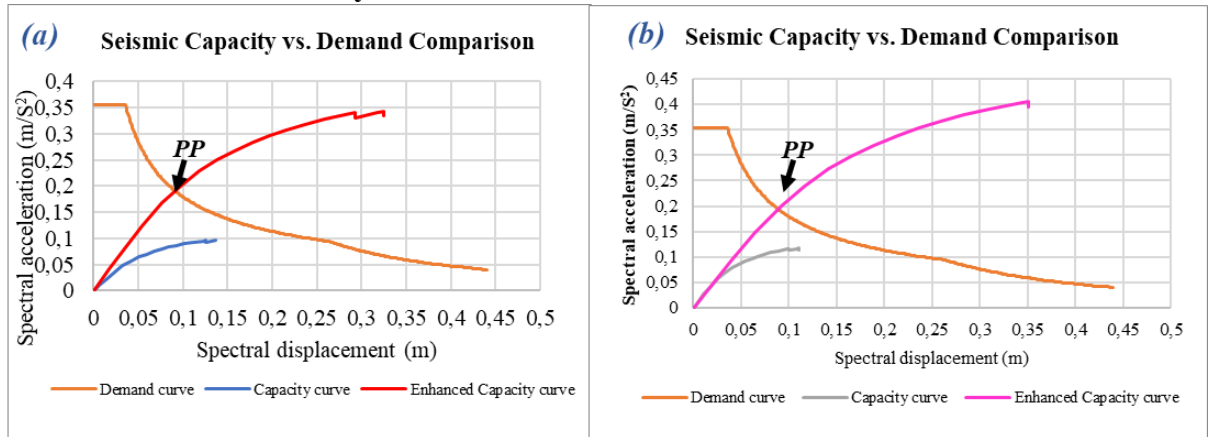


Fig. 5.55 Seismic Capacity and Enhanced Capacity vs. Demand Comparison: X-Direction (a) vs. Y-Direction (b).

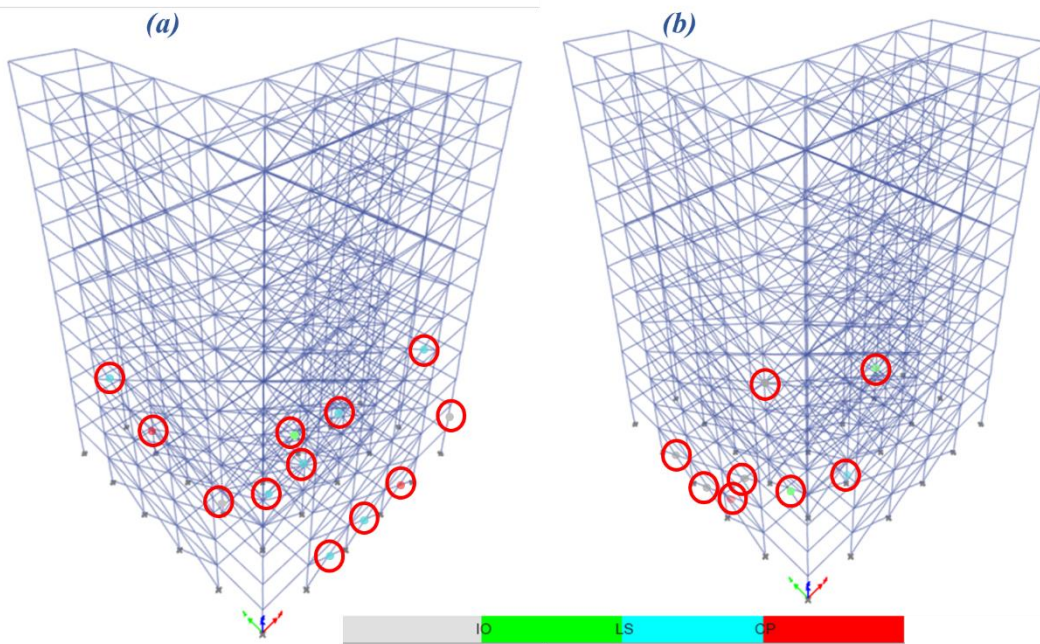


Fig. 5.56 Plastic Hinge Distribution in Retrofitted L-building: X-Direction (a) vs. Y-Direction (b).

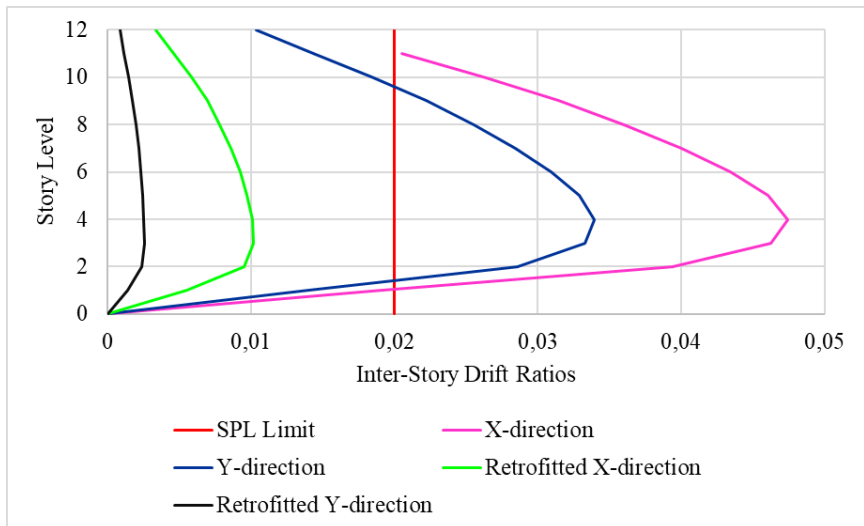


Fig. 5.57 Inter-Story Drift Ratios for Un-Retrofitted vs. Retrofitted in X and Y Directions.

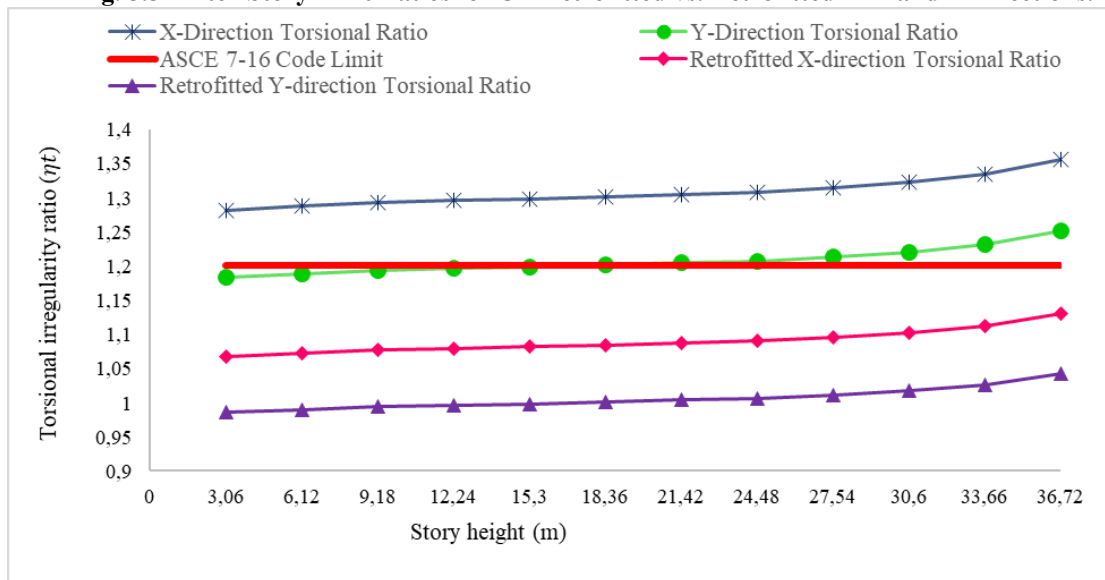


Fig 5.58. Torsional Irregularity Ratios Across Story Height.

Ductility Ratio (μ):

Table 5.45. Ductility Ratios for X and Y Directions.

Direction	Yield Displacement (Δ_{yield} , cm)	Ultimate Displacement ($\Delta_{ultimate}$, cm)	Ductility Ratio ($\mu = \Delta_{ultimate} / \Delta_{yield}$)	RPA99/2003 Code Limit ($\mu \geq 5$)
X-Direction	7,8	22,3	2,86	5,0
Y-Direction	12,9	53,1	4,12	5,0
Retrofitted X-Direction	64,4376	525,696	8,16	5,0
Retrofitted Y-Direction	72,891	693,636	9,52	5,5

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Following the retrofit of the L-shaped RC building with X-brace, the Pushover Analysis results demonstrate a remarkable enhancement in the building's seismic resilience, addressing the critical vulnerabilities identified before the retrofit. Initially, the structure exhibited significant torsional irregularities, particularly in the X-direction, where insufficient lateral stiffness led to low ductility and concentrated plastic hinges in the base columns and beam-column joints. These vulnerabilities, particularly in the upper stories, made the building susceptible to excessive lateral displacements under seismic loading. The introduction of the X-brace system addressed these deficiencies by enhancing the lateral stiffness and improving energy dissipation capacity. As a result, the ductility ratio in the X-direction increased to 8.16, well above the RPA99/2003 code limit of 5.0, confirming the building's improved ability to undergo inelastic deformations without compromising structural integrity. This increase in ductility is a direct indication that the building now has an improved capacity to absorb seismic forces, particularly through the brace elements, which now take on the majority of the inelastic deformation, as opposed to the base columns and beam-column joints. This shift was crucial in redistributing plastic hinges, thus ensuring that the structure would perform better under seismic loading by allowing controlled energy dissipation without progressing to collapse. The performance point for the retrofitted structure, as represented on the capacity vs. demand curve, shows a marked improvement over the un-retrofitted case. In the X-direction, the retrofitted building's capacity curve shifted significantly, intersecting the demand curve at a much higher level, indicating that the structure is now capable of resisting greater seismic forces without experiencing failure. The building now stays within the Life Safety (LS) performance level under higher seismic demands, in contrast to the un-retrofitted structure, which would have failed at lower levels of seismic loading. In the Y-direction, the ductility ratio improved to 9.52, further enhancing the structure's ability to dissipate seismic energy. While the Y-direction initially exhibited fewer vulnerabilities, the retrofit improved its already favorable performance, providing better uniformity in energy dissipation across the structure. The torsional irregularity ratio in both directions was significantly reduced, particularly in the X-direction, where the addition of X-brace eliminated the torsional effects that were previously problematic, ensuring that the building now distributes seismic forces more uniformly. The structure now shows balanced seismic performance with no excessive torsional deformation, indicating that the retrofit strategy effectively addressed the building's initial weaknesses. Overall, the capacity vs. demand comparison and performance point analysis confirm that the retrofitted building is now structurally sound and compliant with seismic safety standards, significantly enhancing its ability to withstand future seismic events while ensuring the safety of its occupants.

Step 04: Post-Rehabilitation Validation for Case Study 3: L-Shaped RC Building with X-Brace Retrofit

Following the application of the Algeria-Specific Seismic Assessment Framework and the retrofitting of the L-shaped RC building with an X-brace system, the Post-Rehabilitation Validation confirms the success of the rehabilitation measures in improving the structure's seismic resilience. This phase validates that the building now meets essential seismic performance levels such as Life Safety (LS), ensuring its ability to withstand seismic forces without compromising occupant safety. The retrofit effectively addresses the vulnerabilities identified during the assessment phases, enhancing the building's overall seismic capacity.

4.1. Results for the L-Shaped RC Building with X-Brace Retrofit:

X-Direction Performance:

- The ductility ratio in the X-direction increased significantly from 2.86 (pre-retrofit) to 8.16 (post-retrofit), exceeding the RPA99/2003 code limit of 5.0, demonstrating that the building now has the capacity to absorb and dissipate much more seismic energy without failing.
- The plastic hinge distribution was shifted from the base columns and beam-column joints to the X-brace system, ensuring that inelastic deformations occur in the braces rather than critical structural elements, effectively preventing progressive collapse.
- Inter-story drift ratios were significantly reduced, and the building now remains within acceptable limits, indicating that the retrofit has effectively enhanced the building's lateral stiffness and its ability to resist excessive deformations.
- Torsional irregularity, which was initially a major concern, has been substantially reduced in the X-direction. The X-brace system has eliminated the previous torsional effects, ensuring that seismic forces are now more uniformly distributed across the structure.

Y-Direction Performance:

- The ductility ratio in the Y-direction improved from 4.12 to 9.52, well exceeding the 5.0 code limit, highlighting the retrofit's success in enhancing the building's ability to resist seismic forces through inelastic deformation.
- Localized weaknesses in the base columns and beam-column joints were addressed through the retrofit, redistributing forces and reducing the risk of localized failures. The overall energy dissipation is now uniform across the structure, further improving seismic performance.

- The torsional stability of the building in the Y-direction was also enhanced, contributing to a more uniform distribution of forces and reducing the potential for torsional damage during seismic events.

4.2. Overall Building Performance:

- The performance point analysis confirmed that the building now meets Life Safety (LS) performance levels, indicating that it can safely undergo significant seismic forces while ensuring occupant safety and preventing collapse.
- The X-brace system has significantly improved both the lateral resistance and torsional stability, providing a robust solution to the building's initial vulnerabilities. The building now performs well under both moderate and strong seismic loading, ensuring that it remains operational and structurally sound after a seismic event.

Step 05: Decision-Making and Final Evaluation for Case Study 3: L-Shaped RC Building with X-Brace Retrofit

The final evaluation step in the Algeria-Specific Seismic Assessment Framework synthesizes all data collected during the rehabilitation process to determine the post-retrofit seismic performance of the L-shaped RC building with X-brace. This phase assesses the building's ability to meet key seismic performance benchmarks, such as Life Safety (LS) and Collapse Prevention (CP), ensuring the structure's resilience and functionality under seismic loading. The building's seismic performance classification is based on comprehensive analysis and post-rehabilitation validation, verifying that the retrofit effectively addresses identified vulnerabilities.

5.1. Seismic Performance Classification

Based on the results of the Pushover Analysis, the ductility improvements, the reduction in torsional irregularities, and the overall energy dissipation capacity of the building, the following seismic performance classification was determined:

L-Shaped RC Building (Post-Retrofit with X-Brace): Life Safety (LS)

The retrofitted building now meets the Life Safety (LS) performance level, ensuring that it remains safe and operational after a seismic event, with no significant risk to the safety of its occupants. Key indicators supporting this classification include:

- **Enhanced Energy Dissipation:** The building's X-brace system has significantly increased its ability to absorb and dissipate seismic energy, ensuring it can undergo inelastic deformations without catastrophic failure.
- **Plastic Hinge Redistribution:** The retrofitting has successfully shifted plastic hinge formation from critical structural elements (base columns and beam-column joints) to

the X-brace system, which is designed to handle inelastic deformation, thereby preventing progressive collapse.

- **Ductility Improvement:** The ductility ratio in both the X and Y directions has increased substantially, with values of 8.16 and 9.52, respectively, which are well above the RPA99/2003 code limits. This indicates that the structure now has a significantly improved capacity to absorb seismic energy without risking structural failure.
- **Torsional Stability:** The retrofit effectively reduced torsional irregularities, ensuring a more uniform distribution of lateral forces and enhancing the building's overall torsional stability.
- **Inter-story Drift:** The inter-story drifts have been reduced and remain within acceptable limits, confirming that the building can resist excessive lateral displacements and maintain its structural integrity even under higher seismic forces.

5.2. Final Evaluation and Decision-Making

After evaluating the results from the Pushover Analysis and post-retrofit validation, the following conclusions and actionable steps are made:

L-Shaped RC Building (Post-Retrofit with X-Brace):

Cleared for Life Safety (LS) Performance Level: The building is now deemed seismically resilient, capable of withstanding significant seismic events without posing a risk to the safety of its occupants. The retrofit ensures structural stability, even under higher seismic forces, and enhances the building's ability to remain operational post-earthquake.

Operational Recovery: After a seismic event, the building is expected to have minimal to no disruption in functionality, ensuring that essential services can resume immediately.

2.5. Recommendations for Ongoing Monitoring and Maintenance

Routine Inspections:

- Conduct periodic visual inspections to ensure the continued effectiveness of the X-brace system and the absence of damage or deterioration in critical components such as braces, base columns, and beam-column joints.
- Regularly monitor the brace system for any signs of wear, corrosion, or fatigue, especially after significant seismic events.

Structural Health Monitoring (SHM):

Implement SHM systems to monitor the structural performance of the L-shaped RC building over time, focusing on high-risk areas such as beam-column joints and base columns.

Continuous monitoring will help track the retrofit's performance and ensure that any future maintenance needs are addressed promptly.

Post-Event Inspections:

Schedule immediate post-event inspections after any significant seismic activity to confirm that the building remains at the Life Safety (LS) performance level, ensuring its structural integrity and occupant safety.

2.6. Regulatory Compliance and Future Use

The retrofitted L-shaped RC building fully complies with RPA99/2003 seismic design codes and is deemed fit for re-occupancy. The Life Safety (LS) classification confirms that the building will ensure occupant safety during an earthquake and remain operational post-event, providing critical functionality for its users. The success of the retrofit highlights its effectiveness in enhancing the building's seismic resilience, making it suitable for continued use in seismic-prone regions.

This final evaluation confirms that the X-brace retrofit has effectively addressed the building's structural vulnerabilities, improved its seismic performance, and ensured compliance with seismic safety standards, safeguarding both the building and its occupants against future seismic events.

5.4 Conclusion

This chapter successfully validated the Algeria-specific seismic assessment framework through real-world and hypothetical case studies, demonstrating its applicability and reliability in evaluating the seismic resilience of reinforced concrete (RC) structures. The validation process, which integrated both quantitative analyses (pushover and nonlinear time history) and qualitative evaluations, confirmed that the framework is capable of identifying and addressing key vulnerabilities in existing buildings. The case studies, such as the Pavilion of Urology at CHU Mustapha Pacha and the Residential Building in the Cité des 1200 Housing Units, provided valuable insights into the effectiveness of various rehabilitation techniques, including advanced materials like FRP and SMA, as well as structural enhancements such as shear walls and fluid viscous dampers.

In each case study, the application of the framework allowed for the identification of critical weaknesses, such as soft-story mechanisms, weak beam-column joints, and insufficient ductility. After retrofitting, these vulnerabilities were significantly mitigated, as evidenced by improved performance in terms of seismic capacity, reduced inter-story drift ratios, and enhanced plastic hinge distributions. The retrofitted structures exhibited superior seismic resilience, achieving performance levels that met or exceeded the expectations outlined in RPA 99/2003, thus ensuring the safety and functionality of the buildings in the event of an earthquake.

Chapter 5: Case Studies and Framework Validation

The results of this chapter provide a solid foundation for the next step in the seismic assessment framework—adapting it to the newly proposed RPA2024. The following chapter will explore the differences between RPA99/2003 and RPA2024, focusing on the new seismic hazard calculations, updated structural response models, and the revised safety and performance criteria. By integrating the advancements presented in RPA2024, the seismic evaluation framework will be further refined to ensure it remains aligned with the latest standards in seismic engineering. This will allow for the continued enhancement of seismic resilience in existing and future reinforced concrete structures across Algeria, addressing evolving seismic risks and improving overall safety in high-risk seismic zones.

*Chapter 6: Impact of
RPA2024 on the Seismic
Assessment Framework
and Case Studies*

*“Between old
provisions and new demands lies progress
— the quiet rewriting of safety...”*

6.1 Introduction

The evolution of seismic design codes is critical to ensuring the resilience of structures in earthquake-prone regions. In Algeria, the devastating impacts of past seismic events, such as the El Asnam earthquake (1980) and the Boumerdes earthquake (2003), have underscored the necessity of continuous advancements in seismic assessment and rehabilitation strategies. Recognizing this need, the Algeria-Specific Seismic Assessment Framework, developed in *Chapter 3*, was designed to provide a systematic methodology for evaluating the seismic performance of reinforced concrete (RC) structures, integrating Algeria-specific seismic parameters, performance-based seismic design (PBSD), and international best practices. The framework was further validated in *Chapter 5*, where case studies demonstrated its applicability under RPA 99/2003, Algeria's previous seismic code.

However, the recent release of RPA 2024 introduces significant revisions in seismic hazard classification, assessment methodologies, and retrofitting provisions, necessitating re-evaluating the framework's validity. Since seismic codes continuously evolve to incorporate advancements in structural engineering, updated hazard models, and lessons from recent earthquakes, it is imperative to assess whether the Algeria-Specific Seismic Assessment Framework remains applicable under the new code or requires modifications to maintain its technical rigor and regulatory compliance. This chapter seeks to verify whether the framework retains its effectiveness under RPA 2024 and to determine whether the required adjustments, if any, are minor refinements or substantial revisions.

To achieve this, this chapter will:

- Compare RPA 99/2003 and RPA 2024, analyzing key updates in seismic hazard zoning, performance-based evaluation criteria, and rehabilitation methodologies that may impact the framework.
- Assess the applicability of the existing framework under RPA 2024 by evaluating whether its core methodologies, performance metrics, and numerical modeling approaches align with the new seismic regulations.
- Apply RPA 2024 provisions to a selected case study and compare the results with previous assessments conducted under RPA 99/2003 to determine whether the seismic capacity, performance levels, or rehabilitation recommendations change under the updated code.

- Categorize the required modifications to the framework as minor (adjustments to parameters and evaluation criteria) or major (fundamental methodological changes requiring redefinition of assessment techniques).
- Propose modifications and final recommendations to ensure the framework remains a reliable, adaptable, and technically rigorous tool for seismic assessment and rehabilitation in Algeria.

By undertaking this verification process, this chapter ensures that the Algeria-Specific Seismic Assessment Framework continues to serve as a robust and effective tool for evaluating RC structures in the Algerian seismic context. Furthermore, this study's findings will provide a roadmap for future adaptations of seismic assessment methodologies in response to evolving regulatory frameworks and seismic hazard models.

6.2 Comparison of RPA 99/2003 and RPA 2024: Identifying Critical Changes

This section provides a detailed comparison of the seismic design provisions in RPA 99/2003 and RPA 2024, highlighting key differences that may affect the existing framework.

6.2.1 Key Changes in Seismic Hazard Classification

6.2.1.1 Seismic Zoning and Peak Ground Acceleration (PGA) Values

One of the most critical updates in RPA 2024 is the refinement of seismic hazard zoning, where the classification has expanded from four seismic zones in RPA 99/2003 to seven zones. Each zone is now associated with a well-defined Peak Ground Acceleration (PGA) value, making hazard assessment more precise and site-specific.

Table 6.1. Comparison of Seismic Zones in RPA 99/2003 and RPA 2024.

Zone	RPA 99/2003 Classification	RPA 2024 Classification	RPA 99/2003 PGA (g)	RPA 2024 PGA (g)
0	Negligible Seismic Risk	Very low	Not Defined	—
I	Low Seismicity	Low		0.07
IIa	Moderate Seismicity	Low to Moderate Seismicity		
IIb	Moderate Seismicity			0.10
III	High Seismicity	Moderate		0.15
IV	—	Moderate to High		0.20
V and VI	—	High		0.25

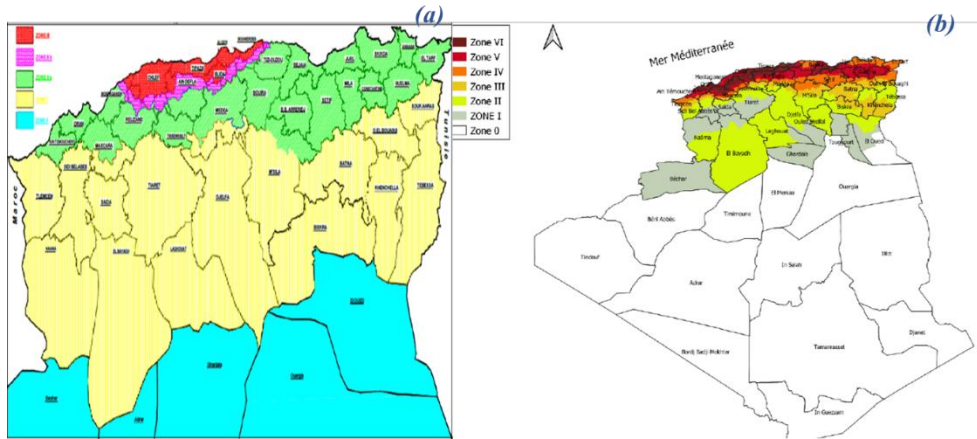


Fig 6.1. Comparison of RPA 99/2003 vs. RPA 2024 seismic zoning maps [3] [4].

6.2.1.2 Spectral Acceleration Parameters

Spectral acceleration $S_{ae}(T)$ is a fundamental parameter in seismic design, defining the maximum acceleration response of a structure normalized by gravitational acceleration (g) for different vibration periods. It forms the basis of the design response spectrum, which guides seismic force calculations in structural engineering. In RPA 99/2003, spectral acceleration values were determined using four seismic zones (0, I, II, III) and a fixed elastic response spectrum. However, RPA 2024 introduces major refinements to the spectral acceleration parameters, compared to RPA 99/2003, including:

- Seven seismic zones (0 to VI) replacing the previous four (0 to III).
- Two elastic response spectrum types (Type 1 and Type 2) based on earthquake magnitude.
- Explicit consideration of site amplification effects using updated site classification coefficients (S).
- New equations for horizontal and vertical spectral response functions.

These updates enhance the accuracy of seismic hazard assessment, directly impacting the Algeria-Specific Seismic Assessment Framework.

A. Updated Elastic Response Spectrum in RPA 2024

The elastic spectral acceleration response in RPA 2024 is given as:

$$\frac{S_{ae}(T)}{g} = A.I.S.F(T) \tag{6.1}$$

Where:

$S_{ae}(T)$: Normalized spectral acceleration (relative to g).

A : Seismic zone acceleration coefficient (Table 6.2).

I : Importance factor (based on building classification, RPA 2024 §3.4).

S : Site amplification factor (Table 3.3 and 3.4).

$F(T)$: Spectral amplification function, defined by period ranges.

B. Spectral Amplification Function $F(T)$:

In RPA 2024, $F(T)$ is given by:

$$F(T) = \begin{cases} \left(1 + \frac{T}{T_1} \cdot (2.5\eta - 1)\right), & 0 < T < T_1 \\ 2.5\eta, & T_1 \leq T \leq T_2 \\ (2.5\eta) \cdot \left(\frac{T_2}{T}\right), & T_2 \leq T \leq T_3 \\ (2.5\eta) \cdot \left(T_2 \cdot \frac{T_3}{T^2}\right), & T_3 \leq T \leq 4S \end{cases} \quad (6.2)$$

Where:

T_1, T_2, T_3 : Period limits defining the spectral shape.

η : Damping correction factor, defined by: $\eta = \sqrt{\frac{7}{2+\xi}}$ (6.3)

with ξ being the damping ratio in percentage (*Table 3.5 RPA2024*).

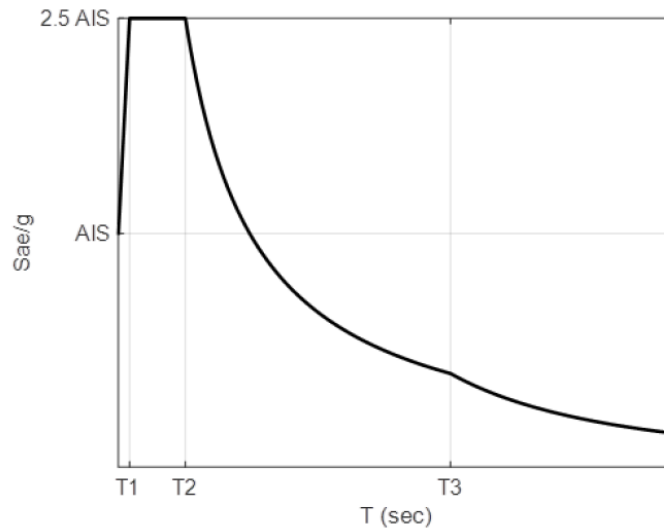


Fig 6.2. Elastic Response Spectrum in RPA 2024.

C. Comparison of Seismic Zone Acceleration Coefficients

The seismic zone acceleration coefficient (A) defines the reference peak ground acceleration (PGA) for seismic design. It is a fundamental parameter in both RPA 99/2003 and RPA 2024, but the methodology used to assign A differs between the two codes.

In *RPA 99/2003*, the seismic zone acceleration coefficient A was not a fixed value for each zone, but varied depending on the building importance category. This means that the same seismic zone could have different acceleration coefficients based on the function of the structure. The formula used was: $A = A_{zone} \cdot I$ (6.4)

This method ensured that essential facilities (hospitals, emergency services, schools) had a higher seismic design acceleration than residential buildings even within the same zone.

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In RPA 2024, the methodology has changed:

A is now assigned strictly based on seismic zone classification, independent of the building's function. The importance factor I is treated separately and applied later in the seismic force calculation. This approach simplifies the assignment of seismic acceleration coefficients and ensures uniform hazard representation across each seismic zone.

Table 6.2 shows the differences in seismic acceleration values between RPA 99/2003 and RPA 2024.

Table 6.2. Comparison of Seismic Zones and Acceleration Coefficients.

Zone	Seismicity Level	RPA 99/2003 A (g) (varied by importance group)	RPA 2024 A (g) (fixed per zone)
0	Very Low	Not considered	Not considered
I	Low	0.07-0.15	0.07 (fixed)
II	Low to Medium	0.10-0.30	0.10 (fixed)
III	Medium	0.18-0.40	0.15 (fixed)
IV	Medium to High	Not Defined	0.20 (fixed)
V	High	Not Defined	0.25 (fixed)
VI	Very High	Not Defined	0.30 (fixed)

D. Site Classification in RPA 99/2003 vs. RPA 2024

RPA 99/2003 classified soil into four categories based on general descriptions of soil stiffness and empirical parameters. However, RPA 2024 introduces an updated classification system that refines soil categories and incorporates shear wave velocity (V_s) as a key parameter for soil characterization. This change allows for a more precise representation of site effects on seismic response.

Table 6.3. Site Classifications in RPA 99/2003 vs. RPA 2024.

Site Class	Description	Shear Wave Velocity (V_s) RPA99/2003	Shear Wave Velocity (V_s) RPA2024
S1	Rock	> 800 m/s	$V_s > 800$ m/s
S2	Firm Soil	400 - 800 m/s	$360 < V_s \leq 800$ m/s
S3	Soft Soil	200-400 m/s	$180 < V_s \leq 360$ m/s
S4	Very Soft Soil	100-200 m/s	$V_s < 180$ m/s

E. Site Amplification Factors S

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The site-dependent amplification factor (S) considers soil conditions, significantly influencing the seismic response.

RPA 2024 introduces a more refined classification system, distinguishing between:

- Spectral Type 1 (for high-seismicity zones: IV, V, VI)
- Spectral Type 2 (for moderate-seismicity zones: I, II, III)

Table 6.4. Site Amplification Factors in RPA 2024 (Spectral Type 1 – Zones IV, V, VI).

Soil Class	Amplification Factor (S)	Period Limits (T_1, T_2, T_3) (s)
S1 (Rock)	1.00	0.10, 0.40, 2.0
S2 (Firm soil)	1.20	0.10, 0.50, 2.0
S3 (Medium soil)	1.30	0.15, 0.60, 2.0
S4 (Soft soil)	1.35	0.15, 0.70, 2.0

Table 6.5. Site Amplification Factors in RPA 2024 (Spectral Type 2 – Zones I, II, III).

Soil Class	Amplification Factor (S)	Period Limits (T_1, T_2, T_3) (s)
S1 (Rock)	1.00	0.05, 0.25, 1.20
S2 (Firm soil)	1.30	0.05, 0.30, 1.20
S3 (Medium soil)	1.55	0.10, 0.40, 1.20
S4 (Soft soil)	1.80	0.10, 0.50, 1.20

F. Vertical Spectral Acceleration

RPA 2024 explicitly defines vertical acceleration effects, which were not fully considered in RPA 99/2003.

$$\frac{S_{ve}}{g}(T) = \begin{cases} A_v \cdot I \cdot \left[1 + \frac{T}{T_1} \cdot (2.5\eta - 1) \right], & 0 \leq T \leq T_1 \\ A_v \cdot I \cdot 2.5\eta, & T_1 \leq T < T_2 \\ A_v \cdot I \cdot [2.5\eta] \cdot \left[\left(\frac{T_2}{T} \right)^\alpha \right], & T_2 \leq T < T_3 \\ A_v \cdot I \cdot [2.5\eta] \cdot \left[\left(\frac{T_3 \cdot T_2}{T^2} \right)^\alpha \right], & T_3 \leq T < 4s \end{cases} \quad (6.5)$$

Where:

$S_{ve}(T)$: Vertical spectral acceleration (g)

A_v : Vertical acceleration coefficient (derived from A , typically $A_v=0.9A$ for **Type 1 spectra** and $A_v=0.55A$ for **Type 2 spectra**)

I : Importance factor

η : Damping correction factor (calculated from Equation 6.3)

α : Exponential factor (depends on soil conditions and spectral type)

T = Vibration period of the structure

T_1, T_2, T_3 : are the period limits that define different regions of the spectrum.

G. Soil-Structure Interaction (SSI) in RPA 99/2003 and RPA 2024

Both RPA 99/2003 and RPA 2024 provide substantial guidelines on soil amplification factors and site classification, but neither code explicitly addresses Soil-Structure Interaction (SSI), which is crucial in understanding how soil-structure systems interact during seismic events. SSI refers to the dynamic interaction between the soil beneath a structure and the structure itself, particularly during an earthquake. The absence of SSI considerations in both codes is a significant gap, as the flexibility of foundations, soil behavior, and resonance effects can alter the seismic response of buildings, especially on soft soils or in liquefaction-prone areas.

6.2.2 Revised Seismic Performance and Design Criteria

The revisions from RPA 99/2003 to RPA 2024 reflect a fundamental shift in the way seismic performance is assessed and integrated into the design process for reinforced concrete (RC) structures. The RPA 2024 introduces more sophisticated design principles such as Performance-Based Seismic Design (PBSD), adjustments to ductility and energy dissipation criteria, and a shift towards more dynamic and realistic load combinations. These modifications ensure that designs are not only safe during an earthquake but also resilient and functional afterward, with a focus on the overall performance of the structure, rather than just on preventing collapse.

6.2.2.1 Integration of Performance-Based Seismic Design (PBSD) and Its Impact on Assessment Methodologies

The introduction of Performance-Based Seismic Design (PBSD) in RPA 2024 marks a significant evolution in the way seismic performance is evaluated. PBSD represents a paradigm shift from the prescriptive design approach used in RPA 99/2003, focusing on the structure's performance objectives under seismic loading rather than simply meeting static force-based requirements.

A. RPA 99/2003 Approach:

In RPA 99/2003, the seismic design process was based largely on prescriptive design methods, focusing on strength and stability to ensure life safety. The seismic forces applied were largely static, using design spectra derived from seismic hazard analysis, which did not explicitly consider how the structure would perform during an earthquake. The seismic design provisions ensured life safety but lacked explicit performance objectives for other key aspects of the structure's behavior, such as functionality post-event or repairability.

B. RPA 2024 Approach:

While RPA 2024 does not explicitly use the term Performance-Based Seismic Design (PBSD), the code embraces principles that are foundational to PBSD, aiming for a more tailored seismic

design approach based on performance objectives rather than prescriptive force-based requirements. This shift is clearly reflected in the code's provisions for performance criteria, seismic demand evaluation, and post-event functionality.

- **Performance Objectives in RPA 2024:**

RPA 2024 defines performance objectives for structures that address multiple levels of performance during and after an earthquake, similar to the core principles of PBSD:

- ✚ Life Safety: The structure must be designed to prevent collapse, ensuring occupants' safety during and immediately after the seismic event.
- ✚ Damage Control: The design must ensure that the structure can absorb energy through nonlinear deformations (e.g., ductility), limiting damage to components, ensuring that the structure remains repairable without significant disruption to the building's functionality.
- ✚ Operational Continuity: For critical infrastructure (e.g., hospitals, emergency centers), the design must ensure that the structure maintains operational functionality after the event, minimizing downtime and ensuring critical services are restored quickly.

These performance levels are established to move away from deterministic design based solely on seismic forces and focus on achieving realistic post-event functionality.

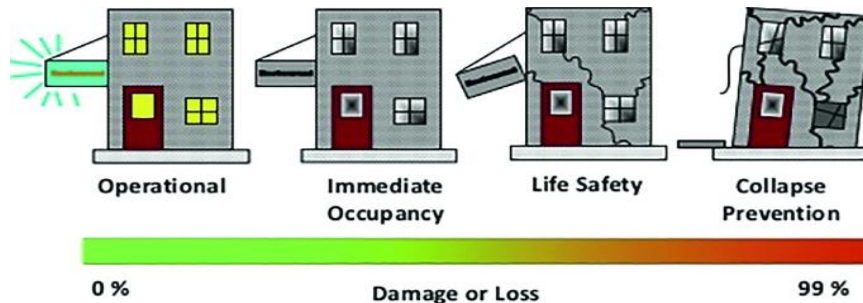


Fig 6.3. Seismic Performance Levels: From Operational to Collapse Prevention [95].

- **PBSD Elements in RPA 2024:**

Nonlinear Time History Analysis:

RPA 2024 encourages the use of nonlinear time history analysis (a method considered essential in PBSD). This analysis simulates the actual response of the structure under dynamic seismic forces, enabling designers to observe how the structure performs during an earthquake, beyond the simple linear elastic analysis. It helps predict:

- Nonlinear deformations,
- Damage accumulation in structural components,
- The structural response under realistic shaking scenarios.

Damage-Based Assessment:

In RPA 2024, performance is assessed using damage-based criteria rather than only strength-based measures. The damage states of structural components are considered to determine whether the building is still safe and repairable after an earthquake. For example, reinforced concrete elements may have defined damage thresholds, where they can tolerate certain levels of plastic deformation without compromising structural integrity. This is integral to PBSB, which relies on understanding damage progression and how it influences the overall structural performance and reparability after the event.

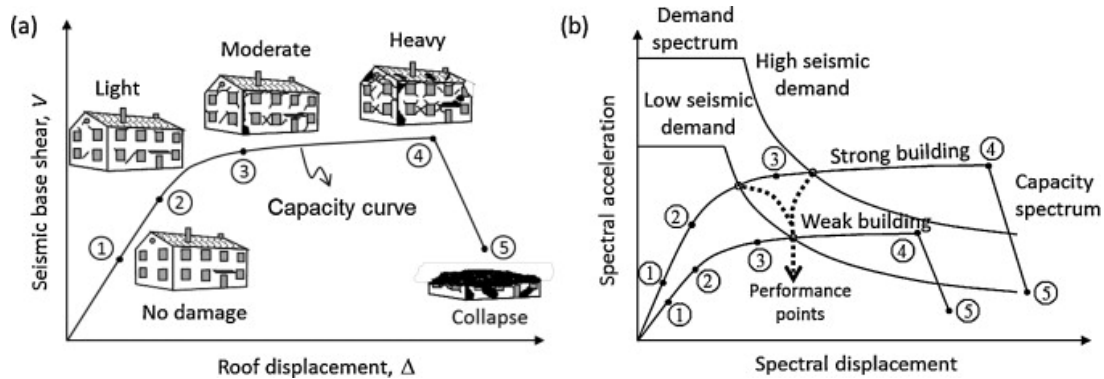


Fig 6.4. Damage States and Performance Evaluation under Seismic Loading [96].

Risk-Based Evaluation:

RPA 2024 introduces risk-based evaluations, acknowledging the uncertainty inherent in seismic loading and soil behavior. Unlike deterministic models, which assume known seismic forces and fixed conditions, the risk-based approach considers:

- Variability in seismic hazard (e.g., earthquakes of different magnitudes, durations, and frequencies),
- This approach allows for the incorporation of a range of scenarios, making the structure's design more robust and ensuring that critical infrastructure can remain functional even under unexpected or extreme conditions.

• Impact on Design Process:

The shift to a PBSB framework in RPA 2024 ensures that seismic demand calculations are not based solely on prescriptive seismic forces but instead incorporate a more dynamic assessment of a structure's seismic behavior.

Engineers can now evaluate the long-term resilience of buildings, considering both damage avoidance and post-event reparability as performance goals.

C. Impact on Assessment Methodologies:

With the shift to PBSB, RPA 2024 requires the integration of advanced seismic analysis techniques such as nonlinear static and dynamic analysis. This results in:

- More accurate modeling of the structural response under realistic seismic loading,

- Customizable performance objectives based on building function, leading to differentiated design strategies for critical infrastructure (hospitals, emergency centers, etc.) versus residential buildings,
- A shift away from deterministic design approaches to probabilistic risk assessments, ensuring that structures are better prepared for a variety of seismic scenarios.

6.2.2.1 Modifications to Ductility, Energy Dissipation, and Structural Resilience Requirements

The ability of a structure to resist seismic forces while maintaining its integrity and post-event functionality is strongly influenced by its ductility, energy dissipation capacity, and resilience. These factors are now more thoroughly integrated into the RPA 2024 design criteria, improving the structure's ability to withstand not just the earthquake but also the recovery process afterward.

A. RPA 99/2003 Ductility and Energy Dissipation:

RPA 99/2003 provided basic ductility requirements for components like reinforced concrete beams and columns, based on strength capacity and the maximum deformation limits to ensure life safety. It included ductility demands but was more conservative in accommodating nonlinear deformations. While energy dissipation mechanisms were acknowledged, their implementation was more general and not as integrated into modern seismic systems (e.g., viscous dampers, base isolators).

B. RPA 2024 Ductility and Energy Dissipation:

RPA 2024 provides more detailed and performance-oriented requirements for ductility and energy dissipation, which are critical for modern seismic-resistant design.

New provisions:

- Nonlinear models to account for energy absorption through ductile behavior of components,
- Consideration of advanced damping systems such as base isolators, ensuring that excessive seismic energy is dissipated without damaging structural components.
- Increased focus on structural resilience, ensuring that buildings can be repaired and made operational with minimal downtime after an earthquake.

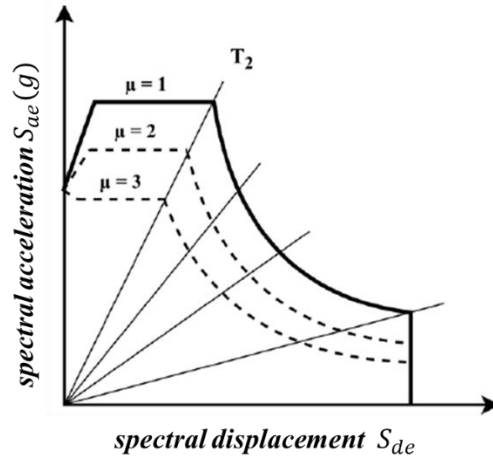


Fig 6.5. Ductility and Energy Dissipation: Spectral Acceleration vs. Spectral Displacement.

6.2.2.3 Changes in Load Combination Factors and Seismic Demand Calculations

The revisions between RPA 99/2003 and RPA 2024 in terms of seismic load combinations and seismic demand calculations reflect a significant shift in seismic design philosophy. RPA 2024 introduces a more dynamic approach to seismic forces and accounts for the vertical seismic component, while RPA 99/2003 was more simplistic and deterministic in its approach. This section outlines the differences in the way seismic forces are combined with other loads (dead loads, live loads) and how seismic demand is calculated, with the introduction of nonlinear analysis methods and dynamic load combinations in RPA 2024.

6.2.2.3.1 Load Combinations in RPA 99/2003 vs. RPA 2024

In RPA 99/2003, seismic action is considered an accidental load, and its combination with other loads follows simpler static equations. The seismic action is typically combined with dead and live loads to evaluate the structural response.

In RPA 2024, the seismic action is divided into three components (two horizontal and one vertical), and the seismic load combinations are more complex. The code introduces the vertical seismic component and requires the use of dynamic load combinations, allowing for a more realistic structural assessment.

A. Load Combination Equations in RPA 2024

In RPA 2024, the seismic action is defined by three components:

- Two horizontal components, E_x and E_y , acting in orthogonal directions,
- One vertical component, E_z , acting along the vertical axis.

The equations for horizontal combinations (E_x and E_y) and vertical seismic action (E_z) are presented as follows:

- **Horizontal Seismic Load Combinations:**

$$\begin{cases} G + \psi Q + E_1 \\ G + \psi Q + E_2 \end{cases} \quad (6.6)$$

Where:

G: Permanent loads (Dead Load),

Q: Variable loads (Live Load),

ψ : Coefficient dependent on the type and duration of the **live load** (given in Table 4.2),

E_1, E_2 are combinations of horizontal seismic components:

$$\begin{cases} E_1 = \pm E_x \pm 0.3E_y \\ E_2 = \pm 0.3E_x \pm E_y \end{cases} \quad (6.7)$$

- **Vertical Seismic Load Combinations:**

For the vertical seismic component, if the product ($A_p \cdot I \cdot g$) exceeds (0.25g), it must be included in the load combinations for specific structural elements such as horizontal elements with spans greater than 15 meters.

The combinations for the vertical component are:

$$\begin{cases} G + \psi Q + E_3 \\ G + \psi Q + E_4 \\ G + \psi Q + E_5 \end{cases} \quad (6.8)$$

where:

- $$\begin{cases} E_3 = \pm E_x \pm 0.3E_y \pm 0.3E_z \\ E_4 = \pm 0.3E_x \pm E_y \pm 0.3E_z \\ E_5 = \pm 0.3E_x \pm 0.3E_y \pm E_z \end{cases} \quad (6.9)$$

- E_3, E_4, E_5 are the seismic actions in the horizontal and vertical directions.

These combinations reflect the need to evaluate the structure under all potential seismic load interactions, including the vertical seismic forces for certain building elements.

B. Load Combinations in RPA 99/2003

RPA 99/2003 simplifies the seismic load combinations by treating seismic action as an accidental load:

$$G + Q + E \quad (6.10)$$

$$0.8G + E \quad (6.11)$$

For specific elements like columns in self-stable frames, a modified combination is used:

$$G + Q + 1.2E \quad (6.12)$$

Where:

- G: Permanent loads,
- Q: Live loads,
- E: Seismic load represented by the horizontal seismic components.

Although vertical seismic effects were not explicitly mentioned, RPA 99/2003 indirectly accounts for them by assuming that a portion of the live load (Q) represents vertical seismic forces.

6.2.3 Updated Retrofitting and Rehabilitation Guidelines

The revisions between RPA 99/2003 and RPA 2024 introduce important advancements in the field of retrofitting and rehabilitation of reinforced concrete (RC) structures. RPA 2024 expands upon the concept of structural resilience by introducing detailed guidelines on the retrofitting of existing structures to meet modern seismic standards, as well as new post-earthquake assessment and repair criteria. RPA 99/2003, on the other hand, is much more limited in its approach and does not include comprehensive provisions for structural retrofitting or repair techniques.

In this section, we will review the modifications and additions introduced in RPA 2024, particularly focusing on the new retrofitting techniques, post-earthquake assessments, and implications for existing versus newly designed buildings. We will also highlight where RPA 99/2003 lacks detailed provisions in these areas.

6.2.3.1 Modifications in Retrofitting Techniques for Reinforced Concrete Structures

The provisions for retrofitting and rehabilitation in RPA 2024 are primarily limited to the design of new structures rather than the rehabilitation of existing buildings. The introduction of base isolation is one of the few updates in RPA 2024 concerning seismic resilience, but it is specifically geared toward newly designed structures rather than existing ones. Unfortunately, RPA 2024 does not offer any clear or comprehensive provisions for retrofitting existing reinforced concrete (RC) structures or for post-earthquake assessment and repair, which remain significant gaps in the code. In contrast, RPA 99/2003 also does not provide any provisions for retrofitting or post-earthquake repair criteria, making both codes insufficient for guiding the rehabilitation of existing infrastructure.

A. Modifications in Retrofitting Techniques for Reinforced Concrete Structures

RPA 2024 introduces base isolation as a seismic design technique, but it is specifically intended for new buildings and does not offer provisions for retrofitting or strengthening existing structures. As outlined in *Chapter 11 of RPA 2024*, base isolation focuses on reducing seismic response by increasing the fundamental period of buildings, which in turn decreases the impact of seismic forces. This technique involves installing base isolators—such as elastomeric bearings or sliding bearings—between the foundation and superstructure of new buildings, effectively decoupling the structure from ground motion during an earthquake. By increasing the building's fundamental period, these isolators reduce the seismic forces acting on the

structure. RPA 2024 provides detailed guidelines for the design and verification of base isolation systems, including specifications for their material properties, rigidity, and damping characteristics. However, while base isolation is a highly effective seismic solution for new buildings, it is not considered a retrofit for existing structures that may have been constructed without seismic considerations. This lack of retrofit guidance in RPA 2024 represents a significant gap in the code, as many older buildings in seismic regions require modern retrofitting to meet the updated seismic standards and ensure their resilience in the event of an earthquake.

B. Post-Earthquake Assessment and Repair Criteria

RPA 2024 lacks a comprehensive framework for post-earthquake assessment and repair criteria for existing structures, providing only a limited mention of pushover analysis as a tool for evaluating structural performance under seismic loads. While the code acknowledges the importance of assessing nonlinear behavior through pushover analysis in new structures, it does not establish clear guidelines for post-earthquake damage assessment, repair prioritization, or rehabilitation protocols. This absence leaves engineers without a systematic approach for evaluating structural integrity and implementing repairs following a seismic event. Additionally, the focus of RPA 2024 remains primarily on the design of new structures, with base isolation explicitly intended for newly constructed buildings rather than the retrofitting of existing ones. Unlike RPA 99/2003, which does not address retrofitting or post-earthquake repair at all, RPA 2024 fails to bridge this critical gap, as it excludes essential guidelines that could facilitate the rehabilitation and seismic resilience of existing infrastructure following a major earthquake. This omission highlights the urgent need for more comprehensive provisions to ensure that both new and existing structures are adequately assessed and repaired after seismic events.

6.2.4 Conclusion: Key Differences Between RPA 99/2003 and RPA 2024

- RPA 2024 introduces significant advancements in seismic design, including an expanded seismic zoning system with more refined peak ground acceleration (PGA) values, replacing the broader classifications of RPA 99/2003.
- Spectral acceleration parameters are revised, incorporating two response spectrum types and explicit site amplification factors, leading to more accurate seismic force calculations.

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- Performance-Based Seismic Design (PBSD) principles are integrated, shifting from prescriptive force-based design to a more tailored approach, emphasizing damage control, operational continuity, and life safety.
- Seismic demand calculations and load combinations now explicitly account for vertical seismic components, offering a more realistic evaluation of structural response under earthquake loading.
- Ductility and energy dissipation criteria are enhanced, incorporating nonlinear deformation modeling and advanced damping systems, improving structural resilience.
- Retrofitting and rehabilitation remain major gaps, as RPA 2024 focuses solely on new structures, with no clear provisions for strengthening existing buildings. While base isolation is introduced, it is limited to new designs, leaving vulnerable structures without modern retrofit strategies.
- Post-earthquake assessment and repair guidelines are lacking, with only a brief mention of pushover analysis, failing to establish a systematic framework for damage evaluation and rehabilitation.
- Soil-Structure Interaction (SSI) is absent in both RPA 99/2003 and RPA 2024, despite its critical role in seismic response modeling, particularly for structures on soft or liquefiable soils.
- Overall, RPA 2024 represents a major step forward in seismic hazard assessment, design methodologies, and performance evaluation, but it still lacks essential provisions for retrofitting, post-earthquake repair, and SSI considerations, highlighting the need for future updates to ensure comprehensive seismic resilience for both new and existing structures.

This section will conclude with a summary of the most critical differences that may impact the applicability of the existing framework. The framework developed in Chapter 3 addresses several gaps in Algeria's seismic assessment practices, notably in its integration of site-specific seismic hazard data, the incorporation of performance-based design principles, and the adoption of advanced rehabilitation techniques such as base isolation and energy dissipation devices. It serves as a comprehensive solution to enhance the seismic resilience of Algeria's reinforced concrete infrastructure, filling the gaps identified in the existing RPA 99/2003. With these advancements, the framework is set to be validated and further refined in subsequent sections, aligning it with the latest seismic standards outlined in RPA 2024, ensuring its practical applicability in Algeria's seismic context.

6.3 Application of the Updated Algeria-Specific Seismic Assessment Framework with RPA 2024 Changes: Case Study Analysis

This section focuses on validating the Algeria-Specific Seismic Assessment Framework by applying it to one of the case studies previously analyzed in *Chapter 5*, integrating the latest updates from RPA 2024. By updating the framework to reflect changes introduced by RPA 2024, we evaluate the structure's seismic vulnerability and performance under the revised code provisions. Through this process, we aim to determine whether the current framework, incorporating RPA 2024 adjustments, remains applicable or requires further modifications.

6.3.1 Selection of the Case Study

To validate the applicability of the *Algeria-Specific Seismic Assessment Framework* under the updated RPA 2024, we have selected “*Block II of the Urology Pavilion at CHU Mustapha Pacha, Algiers (case 01)*”, which includes real-world buildings that have been previously analyzed and evaluated for seismic resilience using the framework developed in *Chapter 3*. This allows us to directly compare the results when the updated RPA 2024 provisions are applied, particularly regarding seismic vulnerability and retrofitting effectiveness. Several factors justify this selection:

- **Critical Infrastructure:** The Urology Pavilion is a vital healthcare facility, making its seismic resilience essential for ensuring uninterrupted medical services post-earthquake.
- **High Seismic Risk:** Located in Algiers, a region prone to seismic activity, this case provides an opportunity to test the framework in a high seismic risk zone.
- **Vulnerability of Older Buildings:** Block II, built before modern seismic codes, is a prime candidate for retrofitting under RPA 2024, allowing us to assess the impact of updated seismic provisions on older, vulnerable structures.
- **Comparison with Previous Assessments:** The building was previously evaluated under earlier codes, enabling a clear comparison of the framework's effectiveness in improving seismic resilience under RPA 2024.

By focusing on this sensitive healthcare facility, the case study demonstrates that if the framework is applicable to such high-priority structures, it will be equally effective when applied to residential or commercial buildings, making it a versatile tool for improving seismic resilience across various building types.

6.3.2 Reassessing the Seismic Performance of Selected Case Study Using RPA 2024

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In this section, we will apply the Algeria-Specific Seismic Assessment Framework (developed in Chapter 3) to the selected case study —*Block II of the Urology Pavilion at CHU Mustapha Pacha, Algiers*, incorporating the updated seismic parameters from RPA 2024. The goal is to validate the framework’s continued applicability by comparing the results obtained under the previous RPA 99/2003 provisions with the updated results from RPA 2024. This comparison will provide insight into the influence of the new seismic hazard classifications, performance criteria, and retrofitting guidelines on the seismic performance of the buildings, ultimately determining if any modifications to the framework are required.

Table 6.6. Key Parameters Changed for the Case Study Under RPA 2024.

Step/Section	Parameter	Case Study 1: Urology Pavilion (BLOCK II)	
		RPA 99/2003	RPA 2024
Step 01: Data Collection	Seismic Zone	Zone III	Zone VI (Extreme Seismicity)
	PGA Value (g)	0.40 (for Zone III and 1A 'building importance category')	0.30 (for Zone VI)
	Soil Class	S ₂ (Firm Soil)	S ₂ (Firm Soil)
	Shear Wave Velocity	V _s : 400 - 800 m/s	360 < V _s ≤ 800 m/s
Step 02: Seismic Performance Evaluation	Seismic Zone Acceleration Coefficient (A)	0.40 (Varied by importance group '1A')	A = Fixed per Zone (e.g., Zone VI = 0.30)
	Site Amplification Factors (S)	Site factors not explicitly defined	1.20 based on soil class and seismic zone
	Load Combinations	Static load combinations (simplified)	Dynamic load combinations (including vertical seismic forces)
	Vertical Seismic Load Combinations (Ez)	Not explicitly mentioned	New vertical seismic load combinations (E ₃ , E ₄ , E ₅) (eq 6.9)

In *Step 01 (Data Collection)* and *Step 02 (Seismic Performance Evaluation)*, the main changes relate to the updated seismic zone classification, PGA values, soil classification, and associated parameters, as clearly outlined in *table 6.6*. These specific updates come from RPA 2024 and

directly affect the inputs required for the seismic assessment. However, it is essential to note that the rest of the information from the case study, including the general building details and previous analysis methodologies from *Chapter 5*, remains unchanged. These unchanged elements continue to serve as the baseline for the comparison, while the new parameters will be incorporated into the assessment.

Moving on to *Step 03: Conduct Updated Seismic Analysis*, we will begin by performing a pushover analysis using the updated load combinations and seismic parameters from RPA 2024. This analysis will assess the building's capacity to resist seismic forces under the new provisions and will be compared to the previous results obtained under RPA 99/2003. The results from the analysis will allow for a clear comparison of the structure's seismic behavior and help us assess whether the updated RPA 2024 parameters require further retrofitting or modifications.

6.3.2.1 Seismic Performance Results of Block II: Comparison Between RPA 99/2003 and RPA 2024

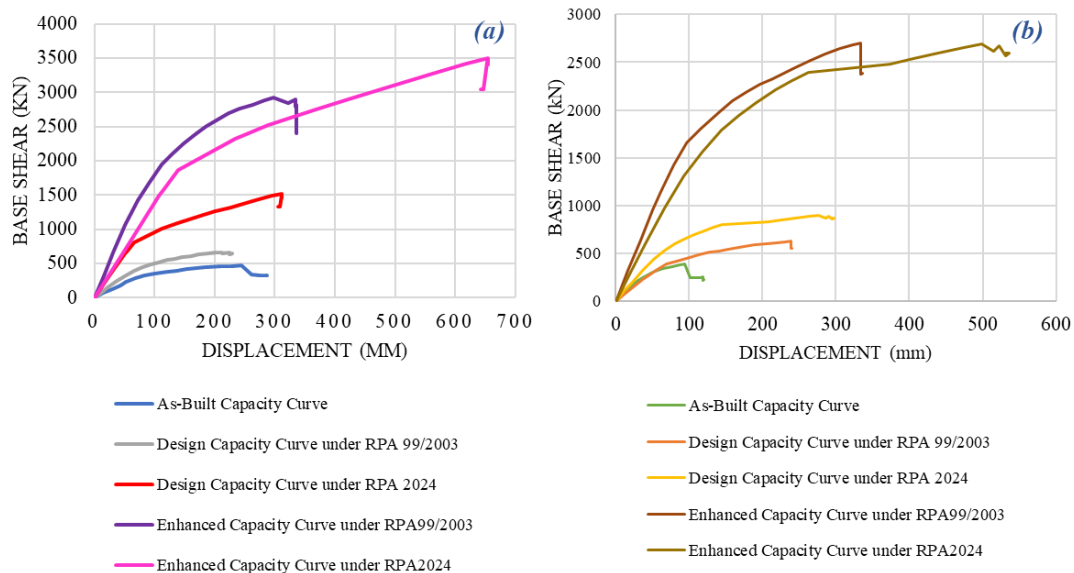


Fig 6.6. Capacity Curves in X (a), and Y(b) Directions for Un-Retrofitted and Retrofitted Structure under RPA 99/2003 and RPA 2024.

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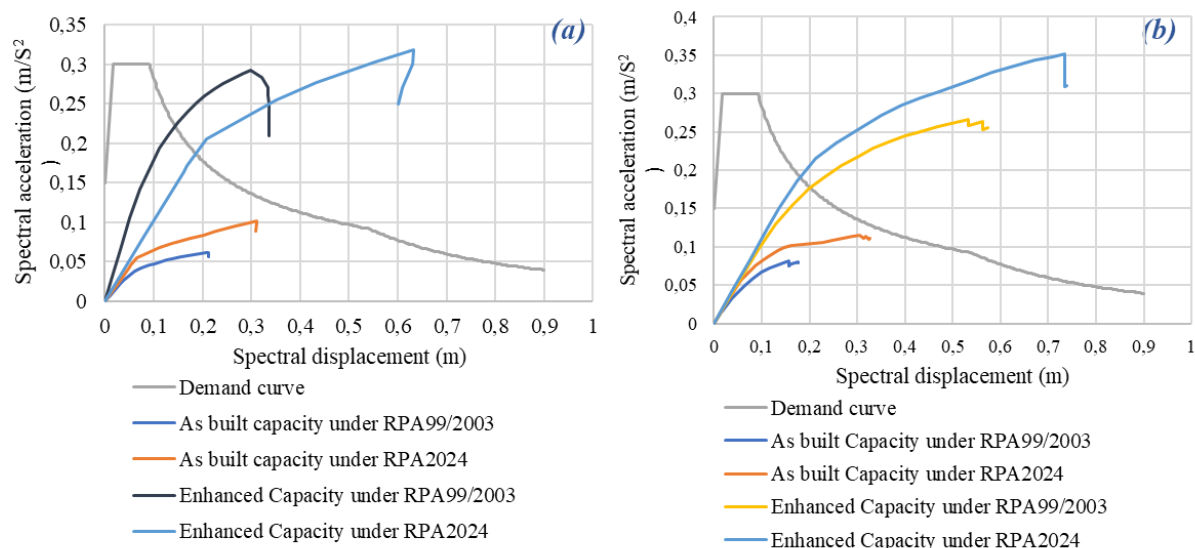


Fig 6.7. Seismic Capacity vs. Demand Curves in the X(a) and Y(b) Directions for Un-Retrofitted and Retrofitted Structure under RPA 99/2003 and RPA 2024.

Table 6.7. Seismic Performance and Hinge Distribution of Block II in the X-Direction Under RPA 99/2003 and RPA 2024.

Case	Performance Point Displacement (mm)	Performance Point Base Shear (kN)	Hinges in IO	Hinges in LS	Hinges in CP	Hinges Beyond CP	Number of Hinges Formed	Location of First Hinge	Final Hinge Distribution
RPA 99/2003 - As-Built	No PP	No PP	81	39	24	34	178	Column bases, beam-column joints	Concentration of hinges in the lower stories where brittle failure occurs due to high seismic demand and vulnerabilities.
RPA 2024 - As-Built	No PP	No PP	29	35	23	15	102	Mid-height column	Slightly fewer CP hinges, increased LS hinges due to lower seismic demand
RPA 99/2003 - Retrofitted	149,1112	2258,76156	06	02	00	00	08	Beam-Column Joints (Ground &	Hinges concentrate in beam-column

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								First Floors).	joints due to stiffness-based design, keeping columns over-strengthened .
RPA 2024 - Retrofitted	208,167624	2058,878949	05	02	00	00	07	Mid-height columns	Hinges redistribute to mid-height columns due to vertical seismic forces and ductility-based retrofitting. No plastic hinges in beam-column joints, ensuring better energy dissipation.

Table 6.8. Seismic Performance and Hinge Distribution of Block II in the Y-Direction Under RPA 99/2003 and RPA 2024.

Case	Performance Point Displacement (mm)	Performance Point Base Shear (kN)	Hinges in IO	Hinges in LS	Hinges in CP	Hinges Beyond CP	Number of Hinges Formed	Location of First Hinge	Final Hinge Distribution
RPA 99/2003 - As-Built	No PP	No PP	102	24	15	05	146	Column bases, beam-column joints	Concentration of hinges in the lower stories due to high seismic demand, resulting in brittle failure and localized vulnerabilities.

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RPA 2024 - As-Built	No PP	No PP	78	24	11	03	116	Mid-height columns	More balanced hinge distribution, with fewer CP hinges. LS hinges dominate, indicating better energy dissipation and less brittle behavior.
RPA 99/2003 - Retrofitted	129,61	2565,127	06	02	00	00	08	Beam-column joints (Ground & First Floors)	Hinges concentrate in beam-column joints due to stiffness-based design, preventing hinge formation in shear walls and columns.
RPA 2024 - Retrofitted	213,6196	1853,321	04	01	00	00	05	Mid-height columns	Hinges redistribute to mid-height columns due to vertical seismic forces. Reduced hinge formation in beam-column joints and shear walls.

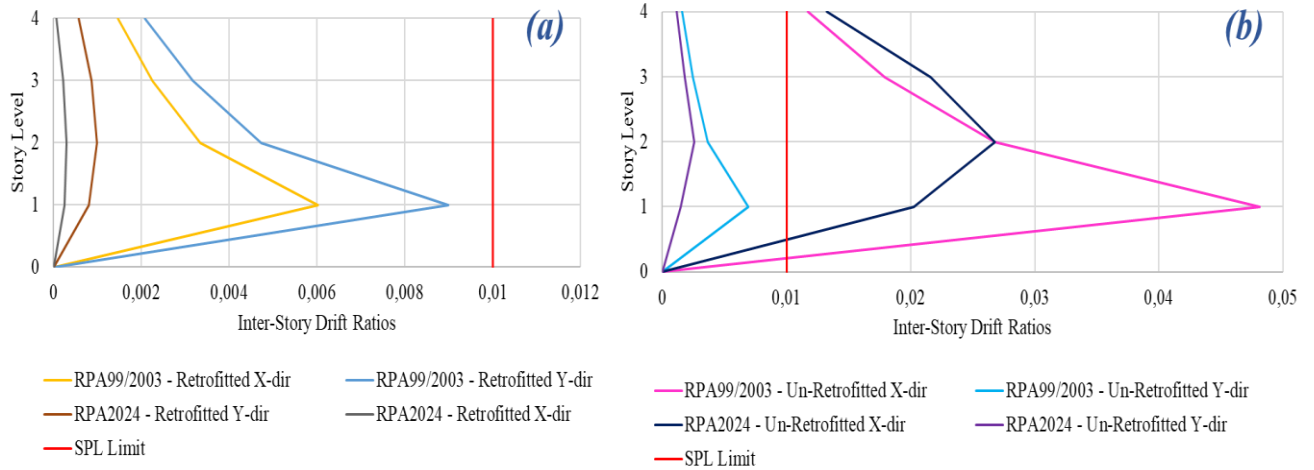


Fig 6.8. Comparison of Inter-Story Drift Ratio Curves for Retrofitted (a) and Un-Retrofitted (b) Structure under RPA 99/2003 and RPA 2024 in X and Y Directions.

6.3.3.2 Interpretation of Seismic Performance Results:

The analysis of *Block II*'s seismic performance under RPA99/2003 and RPA2024 reveals several key improvements driven by the more stringent seismic provisions of RPA2024. These improvements address the building's vulnerabilities, particularly in its lower stories, where brittle failures due to weak beam-column joints and column bases remain a significant concern. Below is a comprehensive interpretation that highlights the differences in seismic performance, the modifications introduced in RPA2024, and how they improve the building's resilience:

- **Increased Seismic Demand Under RPA2024:**

The shift from Zone III to Zone VI and the adjustment of PGA values from 0.40 to 0.30 significantly increase the seismic forces acting on the building. *Block II*'s unretrofitted structure struggles to meet the higher seismic demand under RPA2024, especially in the X-direction, where the demand curve rises significantly compared to RPA99/2003. While RPA2024 shows a better match between capacity and demand, the unretrofitted structure still exhibits a deficit in its ability to handle these forces, exacerbating the building's vulnerabilities.

- **Capacity Improvements in Retrofitted Structure:**

The retrofitted structure under RPA2024 shows a substantial improvement in seismic performance over RPA99/2003, with shear walls and FVD dampers fully optimized to handle the higher seismic forces introduced by the updated seismic hazard classification and PGA values. The base shear resistance significantly increases, and the capacity curve becomes flatter, indicating better energy dissipation and resilience.

- **Hinge Distribution and Structural Vulnerabilities:**

Under RPA99/2003, the unretrofitted structure experiences concentrated hinge formation at beam-column joints and column bases in the lower stories, which are critical vulnerable zones

prone to brittle failure under high seismic demand. These vulnerabilities are less pronounced in RPA2024, where the hinge formation shifts to mid-height columns, reflecting an improvement in the structure's energy dissipation capacity and seismic resilience. This shift indicates that the lower stories are no longer as susceptible to early failures under RPA2024 provisions.

- **Improved Energy Dissipation:**

The unretrofitted structure under RPA2024 still struggles with energy dissipation, leading to rapid increases in inter-story drift that exceed serviceability performance limits. This indicates that Block II continues to lack sufficient lateral stiffness to handle the increased seismic forces. In contrast, the retrofitted structure under RPA2024 benefits from a ductility-based design, which focuses on improving energy dissipation through vertical seismic forces (E_3 , E_4 , E_5) and optimized dynamic load combinations. This results in a gradual transition to nonlinear behavior, a more balanced hinge distribution, and significantly lower inter-story drift ratios, reflecting the effectiveness of the retrofitting measures.

- **Vertical Seismic Forces and Site Amplification Factor:**

The introduction of vertical seismic forces and the updated site amplification factor (1.20) in RPA2024 further contribute to the building's improved seismic response. The site amplification factor accounts for the interaction between soil and structure, increasing the seismic forces acting on the building. In RPA2024, this results in more accurate demand curves, which directly affect the performance of the unretrofitted structure, particularly in the Y-direction, where energy dissipation is more balanced, and hinge distribution is improved compared to RPA99/2003.

- **Key Structural Improvements in Retrofitted Structure:**

Under RPA2024, the retrofitted structure shows that the shear walls and FVD dampers are now more effective in dissipating energy and increasing lateral stiffness. The inter-story drift ratio stays well below the serviceability limits for a broader range of seismic forces, ensuring that the retrofitted structure can withstand higher seismic forces without significant deformation. The retrofitted structure thus represents a more resilient building, able to resist both horizontal and vertical seismic forces with a more gradual transition to nonlinear behavior.

Framework Applicability and Decision on Required Modifications

The analysis of Block II under both RPA99/2003 and RPA2024 demonstrates that the Algeria-Specific Seismic Assessment Framework, remains fully applicable even after the RPA2024 updates. The pushover analysis conducted throughout the assessments provides a solid foundation for evaluating the seismic performance of the building, confirming that the framework continues to offer reliable and accurate seismic evaluations. The updated provisions

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in RPA2024 have enhanced the framework's capability, making it more universal and in line with international seismic codes such as EC8 [6] and ASCE41 [5]. Below is a detailed discussion supporting the continued applicability of the framework:

- The framework proves to be highly adaptable to the updated seismic provisions in RPA2024, which introduces stricter seismic hazard classifications, revised PGA values, dynamic load combinations, and the consideration of vertical seismic forces. These updates improve the seismic demand assessment for the building, making the framework's predictions more reliable and precise. The framework accounts for the increased seismic forces due to the shift from Zone III to Zone VI and the updated site amplification factor, ensuring that the seismic performance of the building is accurately captured.
- Under RPA2024, the framework is strengthened by the introduction of more complex load combinations, including the consideration of vertical seismic forces. These updates enhance the framework's ability to assess energy dissipation and structural resilience. The pushover analysis conducted for both unretrofitted and retrofitted structures demonstrates that the framework provides an accurate evaluation of hinge distribution, energy absorption, and lateral stiffness, reflecting a more resilient structure under modern seismic conditions.
- The framework is designed to be universal and consistent with international best practices for seismic assessment, particularly in regions with high seismic risk. The incorporation of seismic hazard classifications, PGA values, and vertical forces aligns with the principles found in EC8 and ASCE, ensuring that the framework is capable of providing relevant seismic assessments across different global seismic standards. This enhances the framework's applicability beyond Algeria, providing a globally relevant tool for evaluating building performance under various seismic scenarios.
- While the framework remains highly applicable under RPA2024, minor refinements are necessary to fully align it with the updated seismic provisions. These refinements include incorporating the latest seismic hazard parameters, PGA values, and dynamic load combinations from RPA2024, which will further enhance the framework's accuracy in predicting seismic performance and allow it to address the new challenges posed by modern seismic forces. Such minor adjustments are essential for ensuring that the framework stays aligned with current seismic standards.

In conclusion, the Algeria-Specific Seismic Assessment Framework remains robust and applicable under RPA 2024, with only minor adjustments required to fully integrate the updated seismic provisions. These refinements will optimize the framework's seismic assessment capabilities, ensuring its continued relevance and effectiveness for both un-retrofitted and retrofitted structures. The necessary updates include refinements to seismic hazard classification, PGA values, soil classification, and site amplification factors. These adjustments are captured in *Chapter 6, Tables 6.1, 6.2, 6.3, 6.4, and 6.5*, and will enhance the framework's ability to assess seismic risks with greater precision.

6.4 Conclusion

In conclusion, this chapter has rigorously assessed the Algeria-Specific Seismic Assessment Framework in light of the recent updates introduced by RPA2024, confirming that it remains a robust and adaptable tool for seismic evaluation. The comparative analysis between RPA99/2003 and RPA2024, applied to the Urology Pavilion (Block II), highlighted how the updated seismic parameters and performance-based design principles in RPA2024 provide a more precise and reliable framework for assessing building performance. Despite the increased seismic demands under RPA2024, particularly with the shift to Zone VI, the framework has demonstrated its capacity to accurately evaluate energy dissipation, lateral stiffness, and resilience in both unretrofitted and retrofitted structures. The case study outcomes affirm that the framework's core methodologies, including its pushover analysis and performance-based metrics, are still highly applicable and align with the updated code's advanced hazard models and dynamic load combinations. While minor refinements are necessary to incorporate the updated provisions—such as seismic hazard classifications, site amplification factors, and vertical seismic forces—these modifications ensure the framework's relevance and precision. The framework's ability to integrate international best practices positions it as a globally applicable tool for seismic performance evaluation, offering a sustainable solution for improving the seismic resilience of structures not only in Algeria but also in seismic-prone regions worldwide. This chapter confirms that the framework is well-suited for modern seismic challenges and provides a solid foundation for future adaptations as global seismic standards continue to evolve.

Chapter 7:
Conclusions and Perspectives

*“Every study must end, but resilience begins anew — in the questions
left open for tomorrow....”*

7.1 Summary of Key Findings

This research has successfully developed an Algeria-specific seismic assessment framework aimed at improving the seismic resilience of RC structures, particularly those that have undergone rehabilitation. The study addressed the gaps in the existing Algerian Seismic Code (RPA 99/2003) by incorporating advanced assessment methods, modern retrofitting techniques, and PBD principles, which were not sufficiently addressed in the current code.

The key findings of the research can be summarized as follows:

- **Seismic Vulnerabilities of RC Structures in Algeria:** The research confirmed that many RC structures in Algeria, particularly those constructed before implementing modern seismic design codes, exhibit significant vulnerabilities to seismic forces. These weaknesses include inadequate reinforcement detailing, lack of proper energy dissipation mechanisms, and poor foundation designs.
- **Need for Advanced Assessment Techniques:** The study highlighted the need for more sophisticated assessment techniques, such as pushover analysis and nonlinear dynamic analysis, to evaluate the performance of RC structures before and after rehabilitation. These methods proved to be valuable in accurately assessing the seismic capacity of existing structures, providing insights into their potential failure modes, and guiding the implementation of effective retrofitting strategies.
- **Role of Advanced Rehabilitation Methods:** The research explored modern retrofitting techniques, including using FRPs, SMAs, and energy dissipation devices, to enhance the seismic resilience of RC structures. The results demonstrated that these techniques significantly improve the seismic performance of rehabilitated structures, enhancing their strength, ductility, and energy dissipation capabilities.
- **Development of a Tailored Framework:** A comprehensive seismic assessment framework was developed that integrates local seismic hazard data, performance-based seismic design principles, and advanced rehabilitation methods. The framework was validated through case studies of real-world RC structures in Algeria, confirming its effectiveness in assessing and enhancing the seismic resilience of existing buildings.
- **Impact of RPA 2024:** The research also assessed the implications of the newly introduced RPA 2024 seismic code on the developed framework. The comparison between RPA 99/2003 and RPA 2024 highlighted key changes in seismic hazard zoning and rehabilitation provisions, ensuring that the framework remains aligned with the most up-to-date regulations.

7.2 Contributions to the Field

This research makes several significant contributions to the field of seismic engineering in Algeria:

- It bridges the gap between global advancements in seismic assessment and rehabilitation and Algeria's specific infrastructure needs. By incorporating advanced techniques such as pushover analysis, energy dissipation devices, and modern retrofitting materials like FRPs and SMAs, the study provides a scientifically rigorous framework that is practically applicable to Algeria's unique seismic context.
- The development of an Algeria-specific seismic assessment framework provides a valuable tool for engineers and policymakers to evaluate the seismic capacity of existing RC structures and guide rehabilitation efforts. The framework also facilitates the adoption of performance-based seismic design principles, which are crucial for ensuring the safety and functionality of rehabilitated structures under seismic loading.
- The research also contributes to the global discourse on sustainable and cost-effective seismic rehabilitation practices. By evaluating the feasibility of using advanced materials in Algeria's resource-constrained environment, the study provides insights into how innovative solutions can be adapted to local conditions, ensuring both rehabilitated structures' long-term safety and economic viability.

7.3 Implications for Policy and Practice

The findings of this research have important implications for both policy and practice in Algeria's construction and seismic safety sectors:

- **Policy Implications:** The development of the Algeria-specific seismic assessment framework can inform future updates to the national seismic code, RPA 99/2003 and RPA2024, particularly in the areas of post-rehabilitation evaluation, performance-based design, and retrofitting provisions. Policymakers can use the framework to design more robust regulations that align with international best practices while addressing local constraints.
- **Practical Implications:** The study provides practical guidelines for engineers to assess and retrofit existing RC structures. The proposed framework and rehabilitation techniques can be directly applied to enhance the seismic resilience of Algeria's built environment, particularly in high-risk seismic zones. Furthermore, integrating advanced techniques such as pushover analysis and using innovative materials ensures that

engineers can accurately assess structural vulnerabilities and apply effective retrofitting measures.

7.4 Perspectives for Future Research

As seismic resilience continues to be a priority in infrastructure development, several exciting directions for future research can further enhance the field of seismic assessment and rehabilitation:

- **Experimental Validation with Full-Scale Testing:** The framework can be strengthened through large-scale experimental testing of rehabilitated structures using shake tables and other real-world testing methods. Such experiments could provide crucial validation data for the numerical models, especially for complex retrofitting strategies that involve innovative materials like SMAs UHPC. These tests would also help assess the durability of retrofitted buildings under repeated seismic events.
- **Extension to Critical Infrastructure ‘Bridges and Transportation Networks’:** While the current framework effectively addresses multi-story RC buildings, future research could extend its application to critical infrastructure such as bridges, overpasses, and viaducts. These structures present unique challenges due to their dynamic seismic behavior, soil-structure interaction, and the additional complexities posed by traffic loads. Expanding the framework to include these types of infrastructure would significantly enhance the resilience of transportation networks, ensuring their continued functionality during and after seismic events.
- **Application to Steel and Composite Structures:** While the current framework focuses on reinforced concrete (RC) structures, future research could explore its application to steel and composite structures. Steel and composite materials exhibit different seismic behaviors due to their higher ductility and strength compared to RC. Adapting the framework to include these materials would allow for more comprehensive seismic assessments of mixed-use and hybrid structures, which increasingly dominate modern urban infrastructure. This extension would involve developing specific evaluation criteria for the dynamic response of steel and composite elements, incorporating their behavior under seismic loads and their interaction with concrete components in hybrid systems.
- **Integration of Advanced Technologies in Seismic Assessment:** Future research could explore integrating emerging technologies such as Artificial Intelligence (AI) and machine learning algorithms into the seismic assessment process. These technologies

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can potentially optimize the evaluation of structural behavior under seismic loads, predict future vulnerabilities, and automate the identification of weak spots in rehabilitated structures, making assessments more efficient and precise.

- **Expansion of Innovative Retrofitting Materials:** The use of advanced materials, including ultra-high-performance concrete (UHPC), self-healing materials, and smart materials that respond dynamically to seismic forces, could offer exciting opportunities for enhancing buildings' seismic resilience. Research could focus on testing these materials in Algeria's specific seismic conditions to evaluate their long-term effectiveness and feasibility in retrofitting existing structures.
- **Development of Sustainability Models for Seismic Retrofit:** With a growing global emphasis on sustainability, future research can focus on creating models that balance seismic safety with environmental sustainability. This could involve studying the lifecycle environmental impact of retrofitting techniques and materials, such as FRPs and SMAs, and proposing methods to reduce the carbon footprint of seismic rehabilitation while enhancing the resilience of structures.

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Appendix

Appendix

Appendix A: Case Study 1 - Expertise, Non-Destructive Testing (NDT), and Diagnose

Code Inspecteur :		Date :	
IDENTIFICATION DE LA CONSTRUCTION			
Secteur : ALGER Zone : III		Construction calculée au séisme : Oui - (non)	
Adresse : non		Construction contrôlée : Oui - (non)	
Position GPS : X : ; Y : ; Z :			
USAGE DE LA CONSTRUCTION			
Logement	<input type="checkbox"/>	Scolaire	<input checked="" type="checkbox"/>
Administration	<input type="checkbox"/>	Hospitalier	<input type="checkbox"/>
Socioculturel	<input type="checkbox"/>	Sportif	<input type="checkbox"/>
Autres (à préciser) :		Commercial	<input type="checkbox"/>
		Industriel	<input type="checkbox"/>
		Réservoir d'eau	<input type="checkbox"/>
DESCRIPTION SOMMAIRE			
Age approximatif : 65 ans		Vide sanitaire : Oui - (Non)	
Nombre de niveaux : 5		Sous-sol : Oui - (Non)	
Nombre de joints de dilatation : 1			
DOMMAGES VISIBLES SUR LA CONSTRUCTION :			
* Un étage disparu : Oui - (Non)			
* Effondrement total du bâtiment : Oui - (Non)			
PROBLEMES DE SOL AU TOUR DE LA CONSTRUCTION			
* Faïlle : Oui - (Non)		* Liquéfaction : Oui - (Non)	
* Glissement : Oui - (Non)		- Menace la stabilité de la construction <input type="checkbox"/>	
		- Son danger est non négligeable <input type="checkbox"/>	
* Affaissement - soulèvement : Oui - (Non)		- Menace la stabilité de la construction <input type="checkbox"/>	
		- Son danger est non négligeable <input type="checkbox"/>	
FONDATIONS - INFRASTRUCTURE			
Fondations :		Infrastructure (dans le cas VS ou S/Sol)	
- Type de dommages		Voile en béton continu : 1-2-3-	
4-5		Poteaux en béton avec remplissage : 1-2-3-	
- Glissement : Oui - (Non)			
4-5			
- Basculement : Oui - (Non)			
STRUCTURE RESISTANTE			
Eléments porteurs (charges verticales)			
- Murs en maçonnerie		1-2-3-4-5	
- Voiles béton		1-2-3-4-5	
- Poteaux béton		1-2-3-4-5	
- Poteaux métalliques		1-2-3-4-5	
- Poteaux bois		1-2-3-4-5	
- Murs en pierres		1-2-3-4-5	
Planchers - Toiture terrasse			
- Béton armé :		1-2-3-4-5	
- Solives métalliques :		1-2-3-4-5	
- Solives en bois		1-2-3-4-5	
- Autres :		1-2-3-4-5	
Eléments contreventement			
- Murs en maçonnerie		1-2-3-4-5	
- Voiles béton		1-2-3-4-5	
- Portiques béton armé		1-2-3-4-5	
- Portiques métalliques		1-2-3-4-5	
- Palées triangulées		1-2-3-4-5	
- Murs en pierres		1-2-3-4-5	
Toiture inclinée			
- Charpente Métallique :		1-2-3-4-5	
- Charpente en bois :		1-2-3-4-5	
- Couverture amiante-ciment :		1-2-3-4-5	
- Couverture Métallique :		1-2-3-4-5	
- Couverture tuile		1-2-3-4-5	
ELEMENTS SECONDAIRES			
Escaliers			
- Béton :		1-2-3-4-5	
- Métal :		1-2-3-4-5	
- Bois :		1-2-3-4-5	
Autres éléments intérieurs			
- Plafonds :		1-2-3-4-5	
- Cloisons :		1-2-3-4-5	
- Eléments Vitrés :		1-2-3-4-5	
Remplissages extérieurs			
- Maçonnerie :		1-2-3-4-5	
- Béton préfabriqué :		1-2-3-4-5	
- Bardages :		1-2-3-4-5	
- Autres :		1-2-3-4-5	
Eléments extérieurs			
- Balcons :		1-2-3-4-5	
- Garde Corps :		1-2-3-4-5	
- Auvents :		1-2-3-4-5	
- Acrotères - Corniches :		1-2-3-4-5	
- Cheminée :		1-2-3-4-5	
- Autres :		1-2-3-4-5	
INFLUENCE DES CONSTRUCTION ADJACENTES			
La construction menace une autre construction :		Oui - (non)	
La construction est menacée par une autre construction :		Oui - (non)	
La construction peut être soutenue par une autre construction :		Oui - (non)	
La construction peut être un soutien pour une autre construction :		Oui - (non)	
VICTIMS : Oui - Non - (Peut être)		Si Oui combien :	
COMMENTAIRES SUR LA NATURE ET LA CAUSE PROBABLE DES DOMMAGES			
Sens Transversal		Sens Longitudinal	
- Symétrie en plan : (Bon) - Moyen - Mauvais		(Bon) - Moyen - Mauvais	
- Régularité en élévation : (Bon) - Moyen - Mauvais		(Bon) - Moyen - Mauvais	
- Redondances des files : (Bon) - Moyen - Mauvais		(Bon) - Moyen - Mauvais	
AUTRES COMMENTAIRES			
.....			
.....			
.....			
Evaluation finale : -Vert 1- -Vert 2- -Orange 3- (Orange 4) -Rouge 5-			

Fig A.1. Damage Evaluation Sheets Developed by the C.T.C.
Results of Non-Destructive Testing

Appendix

After conducting several non-destructive tests (NDT) on the structural elements of Block I, the results are presented in Table A.1 to Table A.4.

Results for the Ground Floor Columns

Table A.1. Ultrasonic and Rebound Hammer Test Results for Columns (Ground Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
P (10 - C')	3180	3190	3170	3180	17	15,5	16	16,2
P (9 - E)	3115	3120	3105	3113	15	15	15	15
P (5 - A)	3200	3195	3210	3202	16,5	16	17	16,5

Table A.2. Ultrasonic and Rebound Hammer Test Results for Beams (Ground Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
MB-2	3160	3150	3175	3162	17,5	16,5	16	16,7
MB-5	3095	3100	3085	3093	16	15	15,5	15,5
SB-B	3210	3195	3220	3208	16,5	16	16	16,2

Results for the 1st Floor Columns

Table A.3. Ultrasonic and Rebound Hammer Test Results for Columns (1st Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
P (10 - C')	3175	3185	3155	3172	15,5	15.1	16	15,5
P (9 - E)	3100	3110	3105	3105	14,8	14,4	15,2	14,8
P (5 - A)	3205	3195	3215	3205	16	15,5	17	16,2

Table A.4. Ultrasonic and Rebound Hammer Test Results for Beams (1st Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
MB-4	3100	3090	3115	3101	15,5	15	16	15,5
MB-2	3025	3030	3015	3023	14,5	14	15	14,5
SB-B	3145	3130	3160	3145	16	15,5	16,5	16,25

After conducting several non-destructive tests (NDT) on the structural elements of Block II, the results are presented in Table A.5 to Table A.8.

Results for the Ground Floor Columns

Table A.5. Ultrasonic and Rebound Hammer Test Results for Columns (Ground Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
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Appendix

							Test 3 (MPa)	
P (1 - A')	3450	3470	3445	3455	18,5	18	19	18,5
P (3 - C)	3390	3400	3385	3392	17,5	17	18	17,5
P (5 - A)	3505	3495	3520	3507	19	18,5	19,5	19

Table A.6. Ultrasonic and Rebound Hammer Test Results for Beams (Ground Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
MB-4	3420	3405	3435	3420	18	17,5	18,5	18
MB-2	3365	3370	3355	3363	17,5	17	18	17,5
SB-E	3480	3465	3490	3478	18,5	18	19	18,5

Results for the 1st Floor Columns

Table A.7. Ultrasonic and Rebound Hammer Test Results for Columns (1st Floor).

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
P (1 - A')	3440	3455	3430	3442	18	17,5	18,5	18
P (3 - C)	3375	3385	3370	3377	17,5	17	18	17,5
P (5 - A)	3501	3498	3516	3502	18,5	18	19	18,5

Table A.8. Ultrasonic and Rebound Hammer Test Results for Beams (1st Floor)

Column ID	Ultrasonic Test 1 (m/s)	Ultrasonic Test 2 (m/s)	Ultrasonic Test 3 (m/s)	Average Speed (m/s)	Rebound Hammer Test 1 (MPa)	Rebound Hammer Test 2 (MPa)	Rebound Hammer Test 3 (MPa)	Average Strength (MPa)
MB-4	3415	3405	3425	3413	18	17,8	18,2	18
MB-2	3345	3352	3337	3343	17,1	17,9	18	17,7
SB-E	3470	3455	3485	3470	18,4	18,2	19	18,5

Publications Derived from This Research

- 1- Marwa Bakhouche, Rafik Madi, Abderrahim Labeled, & Moufida Gherdaoui. (2025). Seismic Retrofitting of Non-Compliant RC Structures Using SMA Bracings and Modified DDBD: A Parametric Approach. *International Journal of Computational and Experimental Science and Engineering*, 11(4). <https://doi.org/10.22399/ijcesen.4011>.
- 2- Marwa Bakhouche, Rafik Madi, & Moufida Gherdaoui. (2023). Nonlinear Behavior of Irregularly Shaped Reinforced Concrete Buildings with Different X-Bracing Positions. *Tobacco Regulatory Science*, 9(1). <https://doi.org/10.22399/trs.1222>.
- 3- Bakhouche Marwa, Rafik Madi, & Moufida Gherdaoui. (2022). Numerical Analysis of the Behavior of a Reinforced Concrete Beam Strengthened by Various Fibers. Presented at the 2nd International Symposium on Innovative Studies (ISSRIS'22), Bandirma Onyedi Eylul University.
- 4- Bakhouche Marwa, Rafik Madi, & Moufida Gherdaoui. (2022). Pushover Analysis of Multi-Storey RC Building Behavior Under Seismic Load. Presented at the 2nd International Graduate Studies Congress (IGSC), June 8-11, 2022.
- 5- Bakhouche, Marwa, & Madi, Rafik, & Guendouz, Iles. (2023). Pushover Analysis of Gravity Load Designed RC Building with Inverted V-Bracings in ETABS. Presented at the Congrès National de Génie Civil et d'Hydraulique (CNGCH), Guelma, Algeria, December 12-13, 2023
- 6- Marwa Bakhouche, Rafik Madi, Abderrahim Labeled, & Ilyes Guendouz. (2023). Assessing the Influence of X-Bracing Location on Seismic Retrofitting of Regular and Irregular L-Shaped RC Structures: A Parametric Study. 1st International Conference on Civil and Earthquake Engineering (ICCEE 2023), Annaba, Algeria, December 12-14, 2023.
- 7- Bakhouche, Marwa, Madi Rafik, and Labeled Abderrahim. (2024). Seismic Performance of RC Structures: A Comparative Study of Centrally and Eccentrically Bracing Systems. Certificate of Participation, Congrès National de Génie Civil, Tébessa, Algeria.
- 8- Bakhouche Marwa, Rafik Madi, & Moufida GUERDAOUI. (2025). Seismic Rehabilitation of Reinforced Concrete Structures: A Case Study of the Urology Pavilion. Presented at the Congrès National de Génie Civil, Batna, Algeria, December 10-11, 2025.
- 9- Bakhouche Marwa, Rafik Madi, & Moufida GUERDAOUI. (2025). Hybrid SMAP-RP System for Seismic Rehabilitation: A Case Study of the Urology Pavilion at CHU Mustapha Pacha. Presented at the Congrès National de Génie Civil, Guelma, Algeria, December 17-18, 2025.