Palestine Polytechnic University

Deanship Of Graduate Studies And Scientific Research

Master Of Civil Engineering

Nonlinear Seismic Response of Strengthened Reinforced Concrete Frames: A Comparative Finite Element Investigation Using CFRP, RC Jacketing, and UHPC

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Master of Civil Engineering

June , 2026

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Nonlinear Seismic Response of Strengthened Reinforced Concrete Frames: A Comparative Finite Element Investigation Using CFRP, RC Jacketing, and UHPC

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ABSTRACT

This study investigates the seismic performance of reinforced concrete (RC) frames strengthened using different retrofitting techniques under cyclic loading conditions through advanced finite element simulation. A three-dimensional nonlinear finite element model was developed in ABAQUS and calibrated using the experimental results of a previously tested RC frame reported in the literature. Concrete behavior was simulated using the Concrete Damage Plasticity (CDP) model, while reinforcing steel was modeled using an elastoplastic constitutive relationship. The numerical model achieved a high level of agreement with the experimental response, with an accuracy of approximately 95.12% in predicting the peak lateral load, as well as accurately capturing stiffness degradation, crack propagation, and hysteretic behavior. Following validation, three strengthening techniques were investigated, including CFRP strengthening, RC jacketing, and UHPC jacketing. The results demonstrated that all strengthening methods enhanced the seismic behavior of the frame; however, UHPC strengthening exhibited the best overall performance, achieving an increase of approximately 88.5% in load-carrying capacity, 44.73% in ductility, and significant improvement in stiffness and energy dissipation capacity. The findings confirm the effectiveness of advanced strengthening techniques, particularly UHPC jacketing, in improving the seismic resistance and structural performance of deficient RC frames.

الاستجابة الزلزالية اللاخطية للإطارات الخرسانية المسلحة المُدعَّمة: دراسة مقارنة باستخدام العناصر المحددة لتقنيات ألياف الكربون والتغليف الخرساني والخرسانة فائقة الأداء

دنيا فراس قاسم ابوميالة

الخلاصة

تتناول هذه الدراسة تقييم السلوك الزلزالي للإطارات الخرسانية المسلحة (RC) المقواة باستخدام تقنيات تدعيم مختلفة تحت تأثير الأحمال المتكررة، وذلك بالاعتماد على النمذجة العددية المتقدمة باستخدام برنامج ABAQUS. تم تطوير نموذج ثلاثي الأبعاد بطريقة العناصر المحددة ومعايرته اعتمادًا على نتائج تجريبية لإطار خرساني مرجعي منشور في الأدبيات العلمية. جرى تمثيل سلوك الخرسانة باستخدام نموذج اللدونة المتضررة للخرسانة(CDP) ، بينما تم تمثيل حديد التسليح باستخدام نموذج مرن–لدن غير خطي. أظهرت نتائج المعايرة توافقًا عاليًا بين النموذج العددي والنتائج التجريبية بدقة بلغت حوالي 95.12% في توقع الحمل الجانبي الأقصى، إضافةً إلى القدرة على تمثيل تدهور الصلابة وانتشار التشققات والاستجابة الهستيرية بشكل واقعي. بعد التحقق من صحة النموذج، تمت دراسة ثلاث تقنيات تدعيم شملت التدعيم بألياف الكربون(CFRP) ، والتغليف الخرساني، والتغليف باستخدام الخرسانة فائقة الأداء (UHPC). بينت النتائج أن جميع طرق التدعيم حسّنت الأداء الزلزالي للإطار، إلا أن تدعيم باستخدام الخرسانة فائقة الاداء (UHPC) حقق أفضل أداء من حيث زيادة مقاومة الأحمال بنسبة بلغت حوالي 88.5% ، وزيادة الممطولية بنسبة 44.73% ، إضافة إلى تحسين واضح في الصلابة وقدرة المنشأ على تبديد الطاقة، مما يؤكد كفاءة هذه التقنية في تعزيز مقاومة الإطارات الخرسانية للأحمال الزلزالية.

الإهداء

إلى أرواح شهداء فلسطين،
الذين سيبقى أثرهم خالدًا في قلوبنا وذاكرتنا.

إلى روح والدي الشهيد،
أتمنى أن أكون قد وفيتُ بوعدي، وأن يكون هذا الإنجاز امتدادًا لما زرعته في داخلي من قوةٍ وإصرار.

إلى أمي الغالية،
مصدر الدعاء والصبر والمحبة.

إلى أخي، سندي ودعمي الدائم.

وإلى عائلتي وأصدقائي،
شكرًا لكل من كان إلى جانبي في هذه الرحلة.

الشكر والتقدير

أتقدم بجزيل الشكر والتقدير إلى جامعة بوليتكنك فلسطين لما وفرته من بيئة أكاديمية داعمة ساهمت في إنجاز هذا العمل.

كما أتوجه بخالص الامتنان والتقدير إلى مشرفَيّ الدكتور بلال المصري والدكتور هيثم عياد على توجيهاتهما العلمية القيّمة، ودعمهما المستمر، وملاحظاتهما التي كان لها الأثر الكبير في إتمام هذه الرسالة.

وأخص بالشكر المهندس سفيان الترك، الذي كان الداعم الأول خلال هذه الرحلة، وكان لتشجيعه ومساندته الأثر الكبير في الاستمرار وإنجاز هذا العمل، وأنا ممتنة له جدًا على دعمه الدائم.

كما أتقدم بالشكر والتقدير للدكتور نصر عبوشي، الذي كان وما زال قدوتي ومصدر إلهام لي في مجال الهندسة.

وأشكر المهندسة إيناس شويكي لكونها رفيقة داعمة خلال هذه الرحلة.

وفي الختام، أتقدم بالشكر لكل من كان له فضل عليّ، أو قدّم لي معلومة، أو دعمًا، أو كلمة طيبة ساهمت في إنجاز هذا العمل.

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Chapter 1: Introduction

1.1 Background

Reinforced concrete (RC) frame structures constitute one of the most widely adopted structural systems for residential, commercial, and public buildings due to their structural efficiency, durability, and economic feasibility. A considerable portion of the existing RC building stock worldwide, however, was designed according to outdated seismic design provisions or without adequate consideration of modern performance-based seismic requirements. Consequently, numerous existing structures remain vulnerable to earthquake-induced damage, particularly in regions of moderate-to-high seismic hazard. According to Cao et al. [1], Gkournelos et al. [2], and Sarno et al. [3], improving the seismic performance of existing RC structures has become one of the most important challenges in structural engineering because of the increasing demand for resilient infrastructure and the high economic and social consequences associated with structural failure during earthquakes.

Earthquake loading differs fundamentally from gravity loading because it subjects structures to rapidly varying cyclic and reversed lateral forces that continuously change in magnitude and direction. These cyclic actions generate progressive stiffness degradation, cracking, reinforcement yielding, concrete crushing, bond deterioration, and plastic hinge development, eventually leading to strength degradation and possible structural collapse if sufficient ductility and energy dissipation capacity are not provided. As emphasized by Fajfar [4], nonlinear structural response governs the seismic performance of reinforced concrete buildings, making nonlinear analysis indispensable for evaluating structural safety beyond the elastic range. Experimental observations and numerical investigations reported by Shamsi and Sümer [5] and Xie et al. [6] further confirmed that accurate prediction of cyclic degradation mechanisms requires advanced nonlinear constitutive models capable of representing stiffness deterioration, damage accumulation, and material nonlinearity throughout repeated loading cycles.

The seismic response of reinforced concrete frames is governed not only by their global lateral stiffness but also by the strength, ductility, confinement, reinforcement detailing, and deformation capacity of individual structural components. Classical seismic design principles established by Paulay and Priestley [7], together with the displacement-based design philosophy proposed by Priestley et al. [8], demonstrate that ductile structural behavior is essential for preventing brittle failure mechanisms and ensuring sufficient energy dissipation during severe earthquakes. Nevertheless, many existing buildings were designed according to earlier design philosophies that primarily emphasized strength while providing inadequate confinement reinforcement, insufficient transverse reinforcement detailing, and limited deformation capacity. Such deficiencies significantly reduce structural resilience under strong ground motion and often result in premature shear failures, excessive damage concentration, and reduced collapse resistance [2], [3], [7].

To enhance the seismic performance of existing structures, numerous rehabilitation and strengthening techniques have been developed over the past several decades. Conventional approaches such as reinforced concrete (RC) jacketing have long been recognized as reliable methods for increasing member strength, stiffness, and confinement through enlargement of the structural cross-section and additional reinforcement. More recently, externally bonded Carbon Fiber Reinforced Polymer (CFRP) systems have gained widespread acceptance owing to their high strength-to-weight ratio, corrosion resistance, ease of installation, and minimal increase in structural dimensions. In parallel, Ultra-High Performance Concrete (UHPC) has emerged as an advanced strengthening material because of its exceptional compressive strength, tensile resistance, durability, and crack-control capability, making it particularly suitable for seismic rehabilitation applications [9]–[18].

Although extensive experimental investigations have demonstrated the effectiveness of these strengthening techniques, experimental testing remains expensive, time-consuming, and often limited by laboratory size, loading capacity, and instrumentation constraints. Consequently, nonlinear finite element (FE) analysis has become an indispensable research tool for evaluating the seismic behavior of reinforced concrete structures under cyclic loading. Advanced numerical simulations provide detailed insight into stress redistribution, crack development, damage evolution, plastic hinge formation, and failure mechanisms while allowing researchers to investigate numerous strengthening alternatives under identical loading conditions with significantly lower cost than full-scale experimental programs [5], [6], [17].

Among the available numerical approaches, the Concrete Damage Plasticity (CDP) model implemented in ABAQUS has become one of the most widely adopted constitutive models for nonlinear simulation of reinforced concrete structures. The model combines isotropic damaged elasticity with plasticity theory to accurately represent irreversible compressive crushing, tensile cracking, stiffness degradation, and cyclic material response. The theoretical formulation developed by Lubliner et al. [20] and later extended by Lee and Fenves [19] provides the foundation for numerous recent finite element studies involving seismic assessment and strengthening of reinforced concrete structures.

Motivated by these developments, the present study investigates the nonlinear seismic performance of reinforced concrete frames strengthened using three representative rehabilitation techniques, namely RC jacketing, CFRP strengthening, and UHPC jacketing. A unified finite element modeling framework based on ABAQUS and the Concrete Damage Plasticity model is employed to evaluate structural behavior under identical cyclic loading conditions, thereby providing a consistent comparison of the effectiveness of each strengthening technique in terms of strength enhancement, stiffness retention, ductility, damage evolution, and energy dissipation capacity.

1.2 Research Problem and Motivation

Despite the significant progress achieved in seismic design philosophies over the past decades, a considerable proportion of existing reinforced concrete (RC) buildings worldwide continues to exhibit inadequate seismic performance. Many of these structures were designed according to obsolete seismic provisions or without explicit consideration of modern performance-based design concepts. Consequently, deficiencies such as insufficient transverse reinforcement, poor confinement, inadequate joint detailing, strong-beam/weak-column mechanisms, and limited ductility frequently result in severe structural damage during strong earthquake events [1]–[4], [7], [8].

Numerous strengthening techniques have been developed to improve the seismic resistance of existing RC structures. Conventional reinforced concrete (RC) jacketing has demonstrated considerable effectiveness in increasing strength, stiffness, and confinement capacity, although it generally increases member dimensions and structural self-weight [10], [11], [23]. Carbon Fiber Reinforced Polymer (CFRP) systems provide an attractive alternative because of their high strength-to-weight ratio, corrosion resistance, and ease of installation while producing minimal geometric alteration to existing members [9], [12], [13], [26]–[30]. More recently, Ultra-High Performance Concrete (UHPC) has emerged as an advanced rehabilitation material owing to its exceptional mechanical properties, superior durability, and outstanding crack-control capability [14]–[18], [31]–[35].

Although the structural effectiveness of RC jacketing, CFRP strengthening, and UHPC retrofitting has been extensively investigated individually, relatively few studies have compared these techniques within a unified numerical framework employing identical structural configurations, material models, loading protocols, and evaluation criteria. The diversity of experimental conditions, numerical assumptions, constitutive models, and performance indicators adopted in previous investigations makes direct comparison between strengthening techniques difficult and often prevents the establishment of consistent recommendations for practical engineering applications [1], [2], [9]–[18].

Furthermore, the increasing capability of nonlinear finite element analysis has enabled researchers to accurately simulate the cyclic response of reinforced concrete structures while substantially reducing the cost and time associated with large-scale experimental testing. The Concrete Damage Plasticity (CDP) model implemented in ABAQUS has demonstrated remarkable capability in representing concrete cracking, compressive crushing, stiffness degradation, and damage evolution under cyclic loading, making it one of the most reliable constitutive models for seismic assessment of reinforced concrete structures [5], [17], [19], [20]. Nevertheless, the application of a unified CDP-based finite element framework for systematically comparing the seismic performance of RC jacketing, CFRP strengthening, and UHPC jacketing remains limited in the available literature.

Therefore, this study is motivated by the need to establish a comprehensive and consistent numerical comparison of three widely adopted strengthening techniques using identical finite element modeling procedures and cyclic loading conditions. Such an approach enables a more objective evaluation of their relative efficiency in enhancing lateral load capacity, stiffness retention, ductility, damage distribution, and overall seismic performance, thereby providing valuable guidance for selecting appropriate strengthening strategies for existing reinforced concrete structures.

1.3 Research Objectives and Contributions

The primary objective of this research is to evaluate and compare the seismic performance of reinforced concrete frame structures strengthened using three representative rehabilitation techniques, namely reinforced concrete (RC) jacketing, Carbon Fiber Reinforced Polymer (CFRP) strengthening, and Ultra-High Performance Concrete (UHPC) jacketing, through advanced nonlinear finite element analysis performed in ABAQUS.

To achieve this objective, the study pursues the following specific goals:

- To develop a reliable nonlinear finite element model of the reference reinforced concrete frame using the Concrete Damage Plasticity (CDP) constitutive model.
- To validate the numerical modeling strategy against established analytical formulations and published experimental findings.
- To simulate the seismic response of RC frames strengthened using RC jacketing, CFRP strengthening, and UHPC jacketing under identical cyclic loading conditions.
- To compare the structural performance of the investigated strengthening techniques in terms of lateral load capacity, stiffness degradation, ductility, energy dissipation, damage evolution, and failure mechanisms.
- To evaluate the relative advantages and limitations of each strengthening method from structural and practical engineering perspectives.
- To provide numerical evidence that supports the selection of appropriate strengthening techniques for seismic rehabilitation of existing reinforced concrete structures.

The principal contribution of this study lies in establishing a unified numerical framework that enables direct comparison between three major strengthening techniques using identical geometry, material properties, loading history, constitutive models, and performance criteria. Unlike many previous investigations that focused on individual strengthening methods, the present research provides a comprehensive comparative assessment that highlights the relative effectiveness of RC jacketing, CFRP strengthening, and UHPC jacketing within a consistent finite element environment. The findings are expected to contribute to a better understanding of strengthening efficiency and to provide practical guidance for structural engineers involved in seismic rehabilitation and retrofit design.

1.4 Research Gap

Although extensive research has been conducted on RC jacketing, CFRP strengthening, and UHPC retrofitting, most previous investigations have focused on individual strengthening techniques rather than providing a direct comparison among different methods under identical loading and modeling conditions. Furthermore, many studies have primarily emphasized strength enhancement while providing limited evaluation of other important seismic performance indicators such as hysteretic behavior, stiffness degradation, ductility development, energy dissipation capacity, and failure mechanisms.

In addition, the rapid advancement of strengthening materials, particularly UHPC, has created a need for a systematic assessment of their effectiveness relative to conventional strengthening techniques. Although numerous studies have investigated CFRP strengthening, RC jacketing, and UHPC retrofitting independently, direct comparisons among these techniques using the same structural configuration, material assumptions, loading protocol, numerical modeling approach, and performance evaluation criteria remain limited.

Consequently, **a clear research gap** exists regarding the comparative seismic behavior and structural efficiency of RC jacketing, CFRP strengthening, and UHPC jacketing when applied to reinforced concrete frame systems subjected to cyclic loading conditions. Addressing this gap requires a unified analytical framework capable of evaluating the performance of different strengthening techniques under consistent modeling assumptions and assessment criteria.

1.5 Scope of the Study

The present research focuses on the numerical evaluation of the seismic performance of reinforced concrete (RC) frame structures strengthened using three widely adopted rehabilitation techniques: reinforced concrete (RC) jacketing, Carbon Fiber Reinforced Polymer (CFRP) strengthening, and Ultra-High Performance Concrete (UHPC) jacketing. The study is limited to the nonlinear behavior of a representative reinforced concrete frame subjected to quasi-static cyclic lateral loading.

A three-dimensional finite element model was developed using ABAQUS to simulate the structural response of the control frame and the strengthened configurations. Concrete behavior was represented using the Concrete Damage Plasticity (CDP) constitutive model, while reinforcing steel was modeled using an elastic–plastic material model. The same geometric configuration, material properties, boundary conditions, loading protocol, and numerical modeling strategy were maintained for all strengthening alternatives to ensure a consistent and objective comparison.

The evaluation of structural performance is based on key seismic performance indicators, including lateral load capacity, stiffness degradation, ductility, stress distribution, damage evolution, and failure mechanisms. Analytical calculations based on relevant design provisions were also performed to verify the numerical results. The study aims to establish a unified numerical framework for comparing the effectiveness of RC jacketing, CFRP strengthening, and UHPC jacketing in improving the seismic performance of existing reinforced concrete frame structures.

1.6 Research Methodology

This study follows a comparative research methodology to evaluate the seismic performance of reinforced concrete (RC) frame structures strengthened using three rehabilitation techniques: reinforced concrete (RC) jacketing, Carbon Fiber Reinforced Polymer (CFRP) strengthening, and Ultra-High Performance Concrete (UHPC) jacketing. The methodology is based on a systematic literature review, selection of a representative reference frame from published experimental studies, development of strengthening configurations, and comparative assessment of structural performance.

The study began with a comprehensive review of previous research on the seismic behavior of reinforced concrete structures, strengthening techniques, constitutive material models, and finite element simulation approaches. Based on this review, a reference RC frame was selected and modeled using ABAQUS to represent both the control specimen and the strengthened configurations. Concrete behavior was simulated using the Concrete Damage Plasticity (CDP) model, while reinforcing steel was represented by an elastic–plastic constitutive law. Appropriate boundary conditions, interaction definitions, and cyclic loading protocols were applied to reproduce the structural response under seismic-type loading.

Three strengthening schemes were then considered: RC jacketing, CFRP strengthening, and UHPC jacketing. The models were developed under consistent assumptions to ensure a direct comparison of their seismic behavior. The performance of each configuration was evaluated in terms of lateral load capacity, stiffness, ductility, damage distribution, stress development, and energy dissipation.

The obtained results were interpreted by comparing the response of the strengthened models with that of the control frame and by relating the observed behavior to established design provisions and findings reported in the literature. This approach enabled the identification of the most effective strengthening technique for improving the seismic performance of existing reinforced concrete frames.

1.7 Limitations of the Study

The findings of this research should be interpreted within the scope of the adopted numerical methodology and the assumptions employed during model development. The principal limitations of the study are summarized as follows:

- The investigation is limited to nonlinear finite element analysis and does not include full-scale experimental testing.
- The numerical models are based on the geometric configuration and material properties of a representative reinforced concrete frame adopted from published experimental research.
- Only three strengthening techniques are considered, namely RC jacketing, CFRP strengthening, and UHPC jacketing.
- The study investigates structural behavior under quasi-static cyclic loading and does not consider dynamic time-history earthquake analysis.
- Material behavior is simulated using constitutive models available within ABAQUS, particularly the Concrete Damage Plasticity (CDP) model for concrete and an elastic–plastic model for reinforcing steel.
- Environmental effects, long-term deterioration, corrosion, creep, shrinkage, temperature variations, and construction-related uncertainties are beyond the scope of the present investigation.
- The analytical verification is performed using established design provisions and code-based calculations rather than additional experimental validation.

Despite these limitations, the adopted methodology provides a consistent numerical framework for evaluating and comparing the relative effectiveness of the investigated strengthening techniques under identical modeling conditions, thereby providing meaningful insights into their influence on the seismic performance of reinforced concrete frame structures.

1.8 Thesis Organization

This thesis is organized into five chapters.

Chapter 1 introduces the research background by discussing earthquake effects on reinforced concrete structures, seismic strengthening techniques, and the role of nonlinear finite element analysis in seismic assessment. The chapter also identifies the research problem and gap, and presents the objectives, significance, scope, and contributions of the study.

Chapter 2 presents a comprehensive review of previous studies related to the seismic behavior of reinforced concrete frames, strengthening techniques using CFRP, RC jacketing, and UHPC, as well as nonlinear finite element modeling approaches employed in seismic engineering research.

Chapter 3 describes the finite element modeling procedures adopted in ABAQUS, including geometry development, material constitutive models, meshing strategy, boundary conditions, loading protocol, and model validation against experimental results.

Chapter 4 presents and discusses the numerical results obtained from the nonlinear finite element analysis. The chapter evaluates the seismic performance of the strengthened frames in terms of lateral load capacity, hysteretic response, stiffness degradation, ductility, energy dissipation, damage distribution, and failure mechanisms.

Chapter 5 summarizes the major findings and conclusions of the study and provides recommendations for future research and potential applications of the investigated strengthening techniques

Chapter 2: Literature Review

2.1 Seismic Vulnerability and Ductility in RC Frames

Reinforced concrete (RC) frame structures are widely used in seismic regions due to their structural efficiency and architectural flexibility. However, the seismic performance of these structures depends heavily on the interaction between beams, columns, and beam–column joints. Classical seismic design principles established by Paulay and Priestley [7] emphasize that ductile structural behavior is essential for preventing brittle failures and ensuring sufficient energy dissipation during severe earthquakes.

In seismic engineering, ductility is a critical parameter that reflects the ability of a structure to undergo inelastic deformations while maintaining an acceptable load-carrying capacity. To comprehensively evaluate seismic performance, ductility is generally assessed at three complementary levels: material ductility, which describes the inelastic strain capacity of the constituent materials (concrete and steel); element ductility, which refers to the deformation and rotational capacity of individual structural members, such as the formation of plastic hinges in beams and columns; and structural (global) ductility, which represents the overall inelastic lateral displacement capacity of the entire structural system [7], [24]. A structure must possess adequate ductility at all three levels to withstand earthquake-induced demands effectively. The displacement-based design philosophy proposed by Priestley et al. [8] further highlights the necessity of providing sufficient deformation capacity at both the local and global levels to prevent sudden collapse.

Despite these established principles, a considerable portion of the existing RC building stock was designed according to outdated seismic provisions. As a result, many structures exhibit inadequate confinement, insufficient shear resistance, and strong-beam/weak-column mechanisms. Comprehensive reviews by Cao et al. [1] and Gkournelos et al. [2], Sarno et al. [3] emphasized that seismic assessment and retrofitting of existing RC buildings have become critical engineering practices to reduce structural vulnerability. Furthermore, experimental and numerical investigations, such as those conducted by Xie et al. [6], demonstrated that column bases and beam–column joints are highly susceptible to stiffness degradation and plastic hinge formation under cyclic loading. Nonlinear analysis methods, as discussed by Fajfar [4], are indispensable for accurately evaluating the structural safety of these deficient buildings beyond the elastic range, highlighting the need for advanced numerical simulation.

2.2 Finite Element Modeling of RC Structures

Evaluating the nonlinear seismic response and the complex ductility mechanisms of reinforced concrete (RC) structures through full-scale experimental testing is often limited by high costs, extensive testing time, and laboratory constraints. Consequently, numerical simulation based on the Finite Element Method (FEM) has become an indispensable tool for investigating the structural behavior of RC members and frames under seismic loading. Modern finite element software enables researchers to simulate nonlinear material behavior, stiffness degradation, crack propagation, reinforcement yielding, and failure mechanisms with a high level of accuracy while significantly reducing the need for expensive experimental programs.

Several finite element platforms have been widely employed for nonlinear analysis of reinforced concrete structures. Commercial software such as ABAQUS and ANSYS provides advanced material constitutive models and robust nonlinear solution algorithms suitable for detailed three-dimensional simulations. Open-source platforms such as OpenSees are extensively used in earthquake engineering research because of their flexibility in nonlinear structural analysis and performance-based seismic assessment, whereas specialized software such as ATENA is particularly effective for modeling concrete cracking and fracture behavior. In contrast, structural analysis programs such as ETABS are primarily intended for global structural analysis and design, and although they can perform nonlinear analyses, they are generally less suitable for detailed simulation of localized material damage and crack evolution.

Among these numerical platforms, ABAQUS has become one of the most widely adopted software packages for nonlinear analysis of reinforced concrete structures because of its advanced constitutive modeling capabilities, comprehensive nonlinear solution procedures, and reliable implementation of the Concrete Damage Plasticity (CDP) model. These features enable accurate simulation of concrete cracking, compressive crushing, reinforcement yielding, stiffness degradation, damage accumulation, and cyclic hysteretic behavior under complex loading conditions. For these reasons, ABAQUS has been extensively validated against experimental investigations and is frequently employed in seismic assessment and strengthening studies of reinforced concrete structures [5], [6], [17].

Shamsi and Sümer [5] demonstrated that nonlinear finite element models developed in ABAQUS can accurately reproduce the cyclic response of RC frames, including stiffness degradation, strength deterioration, and progressive damage accumulation, provided that appropriate constitutive relationships are adopted. Likewise, Genikomsou and Polak [17] successfully utilized ABAQUS to simulate reinforced concrete structures subjected to cyclic loading, confirming its capability to accurately capture hysteretic response, crack propagation, reinforcement yielding, and ultimate failure mechanisms.

A critical aspect of nonlinear finite element analysis is the selection of an appropriate constitutive model for concrete. Among the available formulations, the Concrete Damage Plasticity (CDP) model has become one of the most widely accepted constitutive models for reinforced concrete subjected to cyclic loading. The theoretical framework of the CDP model originates from the plastic-damage formulation proposed by Lubliner et al. [20], which was subsequently enhanced by Lee and Fenves [19] to incorporate stiffness recovery during load reversals and improve the representation of cyclic loading behavior. Owing to its ability to simultaneously simulate tensile cracking, compressive crushing, irreversible damage evolution, and stiffness degradation, the CDP model has become the preferred constitutive model for nonlinear seismic simulations of RC structures using ABAQUS. Consequently, FEM combined with the CDP model provides a reliable and efficient framework for evaluating and comparing different seismic strengthening techniques.

2.3 CFRP Strengthening Techniques

Externally bonded Carbon Fiber Reinforced Polymer (CFRP) systems have gained widespread acceptance in seismic retrofitting due to their high strength-to-weight ratio, corrosion resistance, and minimal impact on structural geometry. The fundamental mechanism of CFRP strengthening relies on external confinement and crack control. As outlined in the design guidelines of ACI Committee 440 [28] and the fundamental concepts by Teng et al. [26], CFRP jackets restrict the lateral expansion of concrete, thereby enhancing compressive strength and ductility. Furthermore, confinement models developed by Lam and Teng [27] and Ozbakkaloglu and Lim [30] have established the theoretical basis for predicting the behavior of FRP-confined concrete under axial and cyclic loads.

The effectiveness of CFRP in seismic applications has been extensively investigated. One of the earliest experimental studies by Katsumata et al. [12] demonstrated that carbon fiber sheets significantly improve the earthquake resistance of existing RC columns. Subsequently, Zafra and Kawashima [13] showed that CFRP confinement effectively delays concrete crushing and improves the hysteretic response of retrofitted bridge columns. More recent numerical and experimental investigations by Wang et al. [9] confirmed that CFRP strengthening substantially enhances lateral load capacity, crack control, and energy dissipation in RC frames. Additionally, Bournas and Triantafillou [29] highlighted that CFRP jackets are highly effective in preventing longitudinal bar buckling in deficient columns. Overall, the reviewed studies indicate that CFRP strengthening significantly enhances the seismic performance of RC members by improving confinement, delaying crack propagation, and increasing ductility. Nevertheless, its effectiveness may be influenced by debonding behavior and anchorage details.

2.4 RC Jacketing Techniques

Reinforced concrete (RC) jacketing is one of the most traditional and reliable methods for strengthening deficient RC members. The technique involves enlarging the cross-section of an existing member by adding new concrete and supplementary reinforcement. According to Nechevska-Cvetanovska et al. [10] and Elbetar and Issa [11], RC jacketing effectively increases flexural and shear capacities, improves confinement, and enhances global structural stiffness.

The structural effectiveness of RC jacketing relies heavily on the confinement provided by the additional transverse reinforcement. The classical confinement models developed by Mander et al. [21] and Saatcioglu and Razvi [22] demonstrated that lateral restraint significantly improves the compressive strength and post-peak stability of concrete. This explains why RC jackets with closely spaced ties can transform brittle shear failures into more ductile flexural responses. Furthermore, experimental studies by Bousias et al. [23] confirmed that properly detailed RC jackets improve lateral strength, delay stiffness degradation, and enhance energy dissipation. However, as noted by Park and Paulay [24] and Priestley et al. [25], the success of RC jacketing depends strongly on achieving composite action between the old and new concrete, requiring careful surface roughening and proper dowel placement to prevent interface slip. Overall, the literature confirms that RC jacketing is a reliable technique for substantially upgrading the strength, stiffness, and confinement of deficient members. However, its application is often accompanied by increased structural weight, architectural limitations, and constructability challenges.

2.5 UHPC Strengthening Techniques

Ultra-High Performance Concrete (UHPC) has emerged as an advanced material for seismic retrofitting, characterized by exceptional compressive strength, enhanced tensile resistance, and superior crack-control capabilities. According to the foundational work of Richard and Cheyrezy [31] and the comprehensive reports by Graybeal [32], [33], UHPC exhibits remarkable durability and mechanical properties that far exceed those of conventional concrete. The ACI Committee 239 [35] defines UHPC as a composite material with optimized gradation, which, combined with steel fibers, provides significant post-cracking tensile capacity. A state-of-the-art review by Yoo and Banthia [34] further confirmed the superior mechanical performance of ultra-high-performance fiber-reinforced concrete under various loading conditions.

Recent studies have successfully applied UHPC as a jacketing material for seismic strengthening. Zhang et al. [15] investigated the behavior of RC columns strengthened with thin UHPC jackets under cyclic loads, reporting significant improvements in lateral strength and deformation capacity. Similarly, Shao et al. [16] evaluated full-scale UHPC-jacketed RC columns under high axial loads and observed remarkable enhancements in confinement efficiency and ductility. At the joint level, Hung and Hsiao [18] demonstrated that UHPC jackets reinforced with high-strength steel mesh effectively retrofit RC beam-column subassemblies by improving joint shear resistance and delaying crack propagation. Furthermore, Wille et al. [14] highlighted that the fiber-bridging mechanism in UHPC significantly contributes to energy dissipation and post-cracking stability under cyclic loading. Overall, existing research demonstrates that UHPC jacketing provides superior structural enhancements, including exceptional strength, ductility, and crack control. Despite its promising performance, its practical application can be limited by high material costs and specialized construction requirements.

2.6 Research Gap

Although the individual effectiveness of CFRP strengthening, RC jacketing, and UHPC retrofitting has been extensively documented in the literature, a significant research gap persists. Most previous studies have focused on evaluating these techniques independently, often using different structural configurations, material properties, and loading protocols. As highlighted by Cao et al. [1] and Braga et al. [2], direct comparisons among various strengthening methods under consistent numerical modeling conditions remain scarce. Furthermore, while overall seismic performance is frequently emphasized, limited studies provide a unified comparative assessment of key seismic performance indicators—such as hysteretic behavior, ductility, stiffness degradation, and energy dissipation—across these three techniques. Therefore, there is a clear need for a systematic finite element investigation that directly compares CFRP, RC jacketing, and UHPC strengthening within a unified analytical framework under identical geometry, material properties, boundary conditions, and cyclic loading protocols.

2.7 Development of the Present Research

Following the identification of the research gap presented in the previous section, the present study was systematically developed based on experimentally validated structural behavior, verified finite element modeling procedures, and well-established seismic strengthening techniques reported in the literature. Rather than proposing an entirely new structural configuration, the research adopted a benchmark reinforced concrete (RC) frame that had been experimentally investigated under cyclic loading and subsequently validated numerically. Thereafter, three strengthening techniques, namely CFRP strengthening, reinforced concrete (RC) jacketing, and Ultra-High Performance Concrete (UHPC) strengthening, were implemented using experimentally verified material properties and strengthening configurations. This unified methodology ensures that the comparison among the investigated strengthening techniques is conducted under identical structural geometry, loading protocol, numerical assumptions, and boundary conditions.

2.7.1 Selection of the Reference Experimental Model

The reference reinforced concrete frame adopted in the present study was selected from the experimental investigation conducted by Arslan et al. [36], who experimentally evaluated the cyclic behavior of GFRP-strengthened infilled RC frames constructed with both normal- and low-strength concrete. Their experimental program provided comprehensive information regarding the structural dimensions, reinforcement detailing, material properties, loading protocol, instrumentation, and observed failure mechanisms. Owing to the completeness of the experimental database and the reliability of the reported results, this specimen was selected as the benchmark model for developing the finite element simulation adopted in the present study.

2.7.2 Numerical Model Validation

After selecting the reference experimental specimen, the finite element model was developed and validated following the numerical modeling strategy proposed by Shamsi and Sümer [5], who successfully reproduced the cyclic response of reinforced concrete frames using ABAQUS and the Concrete Damage Plasticity (CDP) model. Their investigation demonstrated that the adopted modeling strategy accurately predicts hysteretic behavior, stiffness degradation, crack propagation, and damage accumulation under cyclic loading. Accordingly, the same constitutive modeling approach was adopted in the present study to establish a validated control model before introducing any strengthening technique. The numerical predictions were subsequently compared with the experimental observations reported by Arslan et al. [36] to verify the accuracy of the developed finite element model.

2.7.3 Development of the CFRP Strengthening Model

Following the successful validation of the control frame, the first strengthening scheme was developed using Carbon Fiber Reinforced Polymer (CFRP) sheets. The mechanical properties of the CFRP material, laminate thickness, strengthening configuration, and application regions were adopted from the experimental and numerical investigation conducted by Wang et al. [9]. Their study demonstrated that externally bonded CFRP sheets significantly improve lateral load capacity, initial stiffness, energy dissipation capacity, and cyclic stability while delaying crack propagation and reducing structural damage under earthquake loading. Therefore, the same material properties and strengthening concept were adopted in the present numerical investigation.

2.7.4 Development of the RC Jacketing Model

The reinforced concrete jacketing model was established according to the experimental strengthening procedure presented by Wang et al. [37], who performed a comparative evaluation of RC jacketing, steel jacketing, and base isolation for seismic retrofitting of reinforced concrete frames. Their experimental results showed that RC jacketing substantially increased the lateral strength, stiffness, and deformation capacity of the original frame while improving its overall seismic resistance. Based on these findings, the jacket geometry, reinforcement arrangement, and strengthening concept adopted in the reference study were incorporated into the finite element model developed in the present research.

2.7.5 Development of the UHPC Strengthening Model

The third strengthening technique investigated in this study employed Ultra-High Performance Concrete (UHPC). The strengthening strategy, including the application of UHPC layers and the adopted strengthening configuration, was developed according to the finite element investigation conducted by Al-Huri et al. [38]. In addition, the mechanical properties of UHPC implemented in the numerical model were selected in accordance with the material characterization studies reported by Wille et al. [14], Graybeal [32,33], Yoo and Banthia [34], and the recommendations of ACI Committee 239 [35]. Previous investigations demonstrated that UHPC strengthening provides excellent crack control, higher stiffness, improved load-carrying capacity, and enhanced durability compared with conventional strengthening materials. Consequently, UHPC was selected as the advanced strengthening technique considered in the present comparative investigation.

2.7.6 Summary of the Research Development

Based on the adopted methodology, the present research combines an experimentally verified reinforced concrete frame, a validated nonlinear finite element modeling approach, and three experimentally supported seismic strengthening techniques within a unified analytical framework. Consequently, the seismic performance of CFRP strengthening, RC jacketing, and UHPC strengthening can be evaluated and compared under identical loading conditions, material assumptions, and numerical procedures. The detailed finite element modeling process, constitutive material models, numerical implementation, model validation, and strengthening procedures are presented comprehensively in Chapter 3.

2.8 Comparative Summary of Previous Studies

Table 1 summarizes the principal studies that formed the foundation of the present research. Previous investigations demonstrated that CFRP, RC jacketing, and UHPC strengthening techniques can substantially enhance the seismic performance of reinforced concrete structures. However, most studies evaluated only a single strengthening technique or employed different structural configurations, material properties, loading protocols, and numerical assumptions, making direct comparison difficult. Consequently, the present study integrates experimentally validated finite element modeling with identical structural geometry, loading conditions, and material constitutive models to provide a unified and objective comparison among CFRP strengthening, RC jacketing, and UHPC strengthening techniques.

Table 1 Summary of the Principal References Adopted in the Present Study

Ref.	Authors	Research Type	Strengthening Technique	Main Contribution	Adopted in the Present Study
[36]	Arslan et al. (2019)	Experimental	GFRP strengthening	Experimental cyclic behavior of RC frames	Reference experimental specimen and loading protocol
[5]	Shamsi & Sümer (2024)	Numerical	ABAQUS–CDP	Validated FE modeling methodology	Numerical modeling and validation procedure
[9]	Wang et al. (2023)	Experimental + Numerical	CFRP sheets	CFRP strengthening configuration	CFRP material properties
[37]	Wang et al. (2025)	Experimental	RC Jacketing	Comparative retrofit techniques	RC jacketing configuration
[38]	Al-Huri et al.	Numerical	UHPC	UHPC material modeling	UHPC material properties
[15]	Zhang et al. (2022)	Experimental	UHPC jacket	Cyclic behavior of UHPC strengthened columns	Verification of strengthening effectiveness
[16]	Shao et al. (2021)	Experimental	UHPC jacket	Full-scale cyclic behavior	Interpretation of numerical results

Chapter 3: Development of the Finite Element Model

3.1 Chapter Layout

This chapter presents the finite element modeling methodology adopted in the present study to investigate the seismic behavior of reinforced concrete (RC) frames under cyclic loading. The experimentally validated RC frame obtained from the literature was modeled and analyzed using the finite element software ABAQUS.

The chapter first describes the geometrical configuration of the reference frame, material properties, and constitutive models used for concrete and reinforcing steel. Special attention is given to the Concrete Damage Plasticity (CDP) model and the calibration process adopted to accurately reproduce the experimental response.

Subsequently, the modeling assumptions, boundary conditions, loading protocol, interaction definitions, and meshing strategy are presented. The validation procedure of the numerical model is then discussed through comparison with the available experimental results in terms of load–displacement response, crack propagation, and failure mechanisms.

Finally, the strengthening schemes investigated in the present study, including CFRP strengthening, RC jacketing, and UHPC strengthening, are introduced and described prior to evaluating their influence on the seismic performance of the RC frame.

3.2. Summary of the Experimental Test Program

The reinforced concrete (RC) frame experimentally tested by Arslan *et al.* [36] was adopted as the benchmark case for validating the developed numerical model. The specimen consisted of a one-bay, one-story RC frame subjected to cyclic lateral loading to simulate seismic actions. Figure 1 shown the geometric dimensions and reinforcement details of the tested frame, where structural and foundation dimensions are expressed in centimeters and reinforcement diameters in millimeters. The measured concrete compressive strength $fc' = 25.14\,MPa$, and the modulus of elasticity $E = 28{,}670\,MPa$.

As shown in Figure 2, the damage evolution under cyclic loading was primarily concentrated at the column bases and beam–column joint regions. Initial cracking appeared in the form of vertical flexural cracks at the bottom of the columns within the maximum moment regions, resulting from tensile stresses exceeding the concrete tensile capacity. With the progression of loading cycles, the cracks propagated upward and increased in width, leading to the formation of plastic hinge regions at the column bases. Moreover, localized damage was observed in the beam–column joint zones, indicating a gradual transition from predominantly elastic behavior to nonlinear response characterized by stiffness degradation and strength deterioration under repeated cyclic loading.

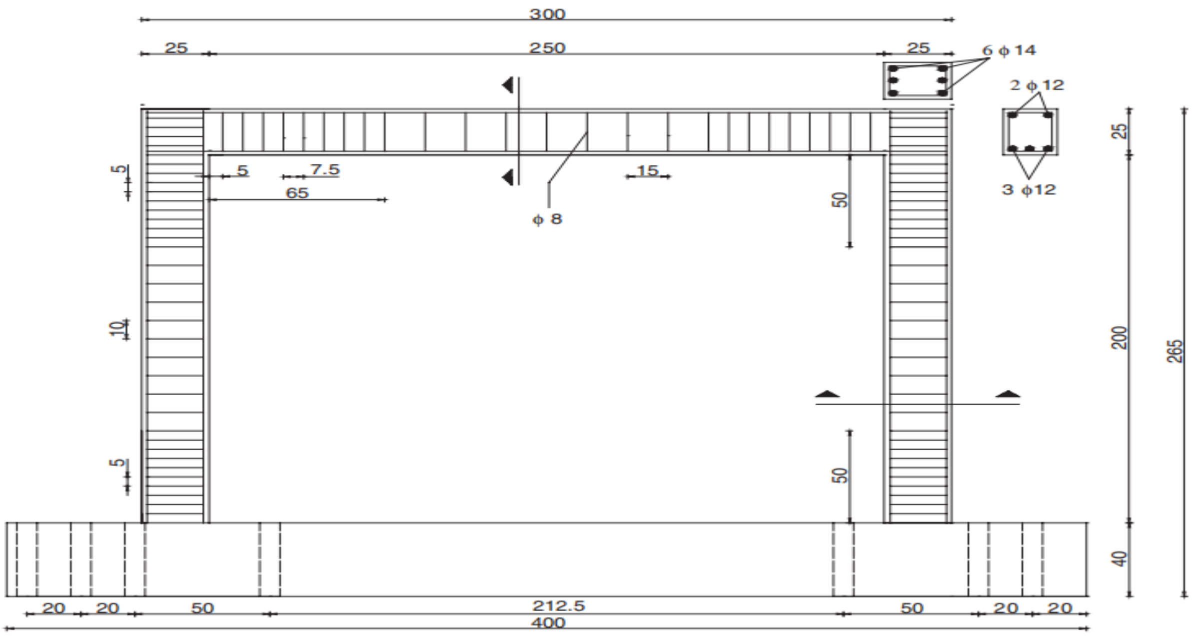


Figure 1 Dimensions and reinforcement details of the test frame . [36]

Figure 2 Failure pattern of the tested frame . [36]

3.3 Development of the Finite Element Model

To reproduce the experimental investigation within a numerical framework, a three-dimensional nonlinear finite element model was developed using the commercial finite element package ABAQUS. The modeling methodology, including constitutive material modeling, calibration procedures, and validation against the experimental cyclic response, was primarily based on the finite element framework proposed by Shamsi and Sümer [5], whose validated ABAQUS modeling approach served as the principal reference for the numerical simulation conducted in the present study.

Nonlinear cyclic analysis was performed to simulate the structural response of the tested reinforced concrete frame subjected to reversed lateral loading. Concrete was discretized using eight-node linear brick elements with reduced integration (C3D8R), which were selected because of their computational efficiency and proven capability to accurately represent the nonlinear stress–strain behavior of concrete under cyclic loading.

Since the structural response was governed by repeated load reversals, particular attention was devoted to accurately reproducing stiffness degradation, crack initiation and propagation, crack opening–closing mechanisms, and hysteretic energy dissipation. Accordingly, the stiffness recovery parameters incorporated in the Concrete Damage Plasticity (CDP) model were carefully calibrated to reproduce the experimentally observed unloading and reloading behavior, stiffness deterioration, and cyclic energy dissipation.

The nonlinear mechanical behavior of concrete was represented using the Concrete Damage Plasticity (CDP) constitutive model available in ABAQUS, whereas the reinforcing steel bars were modeled explicitly to capture their nonlinear inelastic response under cyclic loading. The constitutive formulation, material parameters, and calibration procedure adopted for the CDP model are presented in the following section.

3.4 Constitutive Material Models

A three-dimensional continuum damage–plasticity formulation was employed to represent the nonlinear behavior of concrete. The Concrete Damage Plasticity (CDP) model available in ABAQUS was adopted to simulate the material response under cyclic loading conditions. This constitutive framework combines classical plasticity theory with damage mechanics to capture stiffness degradation resulting from tensile cracking and compressive crushing.

The CDP model enables accurate representation of concrete behavior in various structural components, particularly solid elements used in nonlinear finite element analysis. Its formulation accounts for plastic flow, compressive hardening and softening, tensile cracking, and progressive degradation of elastic stiffness.

3.4.1 Concrete Plasticity

The plasticity formulation of the CDP model is governed by several material parameters that control the yield surface characteristics and the plastic flow potential. These include the dilation angle (φ), the eccentricity parameter (ε) associated with the Drucker–Prager hyperbolic flow function, the ratio of initial biaxial to uniaxial compressive strength (fb'/fc'), the deviatoric plane shape factor (K_c), and the viscosity parameter (μ), which enhances numerical stability in nonlinear cyclic analysis.

The plasticity parameters adopted for the Concrete Damage Plasticity (CDP) model are summarized in **Table 2**. Among these parameters, the values of K_c and fb'/fc'were calculated using Eqs. (1) and (2), respectively, based on the relationships proposed by the researcher referenced in [5]. The remaining plasticity parameters were selected in accordance with widely accepted recommendations reported in the literature for the nonlinear finite element modeling of reinforced concrete. Collectively, these parameters govern the plastic flow characteristics of concrete and play a crucial role in defining dilation behavior, confinement sensitivity, yield surface evolution, and the post-yield response under cyclic loading.

$$K_c = 0.71(fc')^{-0.025} \qquad 1$$

$$\frac{fb'}{fc'} = 1.57(fc')^{-0.09} \qquad 2$$

Table 2 Concrete Damage Plasticity (CDP) Parameters

Parameter	Symbol	Value	Description
Dilation Angle	ϕ	20°	Controls volumetric expansion under shear
Eccentricity	ε	0.1	Flow potential eccentricity parameter
Biaxial/Uniaxial Strength Ratio	fb'/fc'	1.175	Ratio of initial biaxial to uniaxial compressive strength
Deviatoric Shape Factor	K_c	0.655	Yield surface shape factor in deviatoric plane
Viscosity Parameter	μ	0.001	Numerical stabilization parameter

3.4.2 Concrete Compressive Behavior

To accurately represent the compressive response of concrete under cyclic loading, the well-established stress–strain formulation proposed by Carreira and Chu [39] was adopted in this study . This constitutive model is widely recognized in nonlinear finite element analysis of reinforced concrete due to its ability to realistically capture both the ascending and descending branches of the compressive stress–strain curve.

The adopted formulation defines the nonlinear compressive behavior as a function of the concrete compressive strength, the corresponding strain at peak stress, and the elastic properties of the material. The model parameters governing the curve shape and post-peak softening were calculated according to the established relationships provided in the referenced formulation. These expressions account for the influence of material stiffness, secant modulus, and strength level on the overall compressive response.

The resulting stress–strain relationship was implemented within the Concrete Damage Plasticity framework to ensure consistent representation of stiffness degradation and inelastic deformation under cyclic loading. The calculated parameters used in the present study are summarized in Table 3.

3.4.3 Concrete Tensile Behavior

The tensile behavior of concrete was assumed to follow a linear elastic response up to the tensile strength, as illustrated in Figure 3. Cracking is initiated once the tensile stress reaches the concrete tensile strength f_{ct}.

Since the tensile strength was not explicitly reported in the experimental reference, it was calculated according to the CEB-FIB 2010 Model Code [40], as expressed in Eq. (3). In addition, the fracture energy G_f , which represents the energy required to create a unit crack surface, was determined using the corresponding code-based formulation given in Eq. (4).

$$f_{ct} = 1.4\left(\frac{fc' - 8}{10}\right)^{2/3} \qquad 3$$

$$G_f = 0.073(fc')^{0.18} \qquad 4$$

To mitigate mesh sensitivity associated with strain-softening formulations, the post-cracking tensile response was defined in terms of a stress–crack opening displacement relationship ($f_{ct} - \omega$). Among the available softening models reported in the literature—linear, bilinear, and exponential—the bilinear tension softening model illustrated in Figure 3 was adopted in this study. This formulation enables a realistic representation of stiffness degradation and crack propagation under cyclic loading conditions.

Furthermore, in accordance with ABAQUS numerical implementation requirements, a lower bound was imposed on the residual tensile stress to ensure stable convergence during the unloading and reloading phases.

The calculated tensile strength, fracture energy, and post-cracking parameters derived from Eqs. (3) and (4) are summarized in Table 3, which will be presented following the description of the damage parameters.

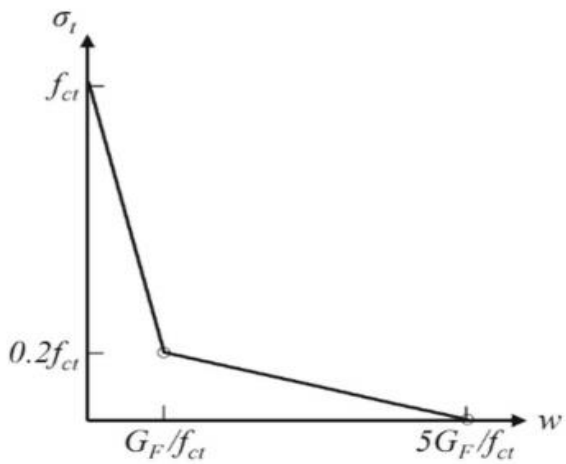


Figure 3 Bilinear tensile [5]

3.4.4 Concrete Damage Modeling

The degradation of concrete stiffness under both tensile and compressive loading was modeled using the damage formulation incorporated within the Concrete Damaged Plasticity (CDP) framework. The adopted uniaxial stress–strain relationships are illustrated in Figure 4. According to Eq. (5), the total strain is decomposed into elastic and inelastic components, allowing the representation of irreversible deformation after cracking or crushing.

$$\varepsilon = \varepsilon_{el} + \varepsilon_{in} = \frac{\sigma}{E_c} + \varepsilon_{in} \quad 5$$

Material degradation is introduced through a scalar damage variable that progressively reduces the effective elastic stiffness. As expressed in Eq. (6) , the initial elastic modulus E_c is modified by the damage parameter d , resulting in an effective stiffness $E_{cs} = (1 - d)E_c$. This formulation enables the simulation of stiffness deterioration associated with micro-cracking in tension and micro-crushing in compression.

$$E_{cs} = (1 - d)E_c \quad 6$$

Under tensile loading, stiffness degradation initiates after the onset of cracking and is governed by the tensile damage variable d_t , defined according to Eq. (7). The evolution of d_t controls the descending branch of the tensile stress–strain response shown in Figure 4, reflecting the progressive reduction in load-carrying capacity due to crack propagation and widening.

$$d_t = \frac{\varepsilon_t^{\sim cr}}{\varepsilon_t^{\sim in} + \frac{5\sigma_t}{E_c}} \leq 0.8 \qquad 7$$

Similarly, under compressive loading, post-peak softening and crushing behavior are governed by the compressive damage variable d_c, defined according to Eq. (8). The parameter d_c represents the gradual deterioration of the concrete matrix after reaching peak compressive stress and controls the compressive softening response illustrated in Figure 4.

$$d_c = \frac{\varepsilon_c^{\sim in}}{\varepsilon_t^{\sim in} + \frac{2\sigma_c}{E_c}} \leq 0.8 \qquad 8$$

To ensure thermodynamic consistency and prevent artificial stiffness recovery during unloading–reloading cycles, the equivalent plastic strains were calculated in accordance with Eq. (9). This approach guarantees numerical stability and realistic simulation of nonlinear degradation behavior.

The calibrated compressive damage coefficients d_c adopted in the numerical model are summarized in Table 3, while the tensile damage coefficients d_t are presented in Table 4. Both sets of parameters were defined consistently with the corresponding stress–strain responses and implemented using the same calibration methodology within the CDP model.

$$\varepsilon_c^{\sim pl} = \varepsilon_c^{\sim in} - \frac{d_c}{(1 - d_c)} \frac{\sigma_c}{E_c} \qquad 9$$

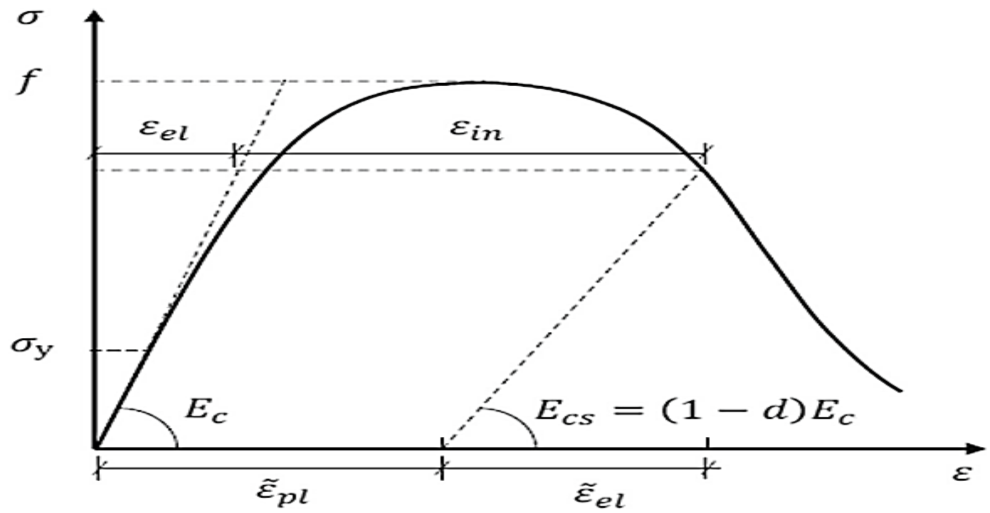


Figure 4 Damage progression of the concrete [5]

Table 3 Compressive Stress–Inelastic Strain–Damage Parameters (d_c) Adopted in the CDP Model

Compressive Stress	Inelastic Strain	Damage Parameter
0	0	0
3.195056023	0	0
9.191594929	0	0
14.47602827	1.0081E-05	0.009884099
18.71388414	6.7266E-05	0.049001472
21.783911	0.000165184	0.098043066
23.75272465	0.000301513	0.153951956
24.79879189	0.000470026	0.213650951
25.13703694	0.000663229	0.274427511
24.78612159	0.000880468	0.337404755
23.70262471	0.00112326	0.404524926
22.15404065	0.001382274	0.472132538
20.37550184	0.001649309	0.537113467
18.54058938	0.00191831	0.597290124
16.7613402	0.00218537	0.651448926
15.10073068	0.002448292	0.699170596
13.58762374	0.002706068	0.740590796
12.22944156	0.002958441	0.776176181
11.02132862	0.00320558	0.806552791
9.952164842	0.003447872	0.832391388
9.008241015	0.003685796	0.854339573

Table 4 Tensile Stress–Cracking Strain–Damage Parameters (d_t) Adopted in the CDP Model .

Tensile Stress	Cracking Strain	Damage Parameter
1.754893159	0	0
0.350978632	0.074325515	0.8
0.017548932	0.371627576	0.99

3.4.5 Modeling of Steel Reinforcement

Steel reinforcement was modeled to accurately represent the nonlinear behavior of the longitudinal and transverse reinforcement bars embedded within the concrete matrix. As illustrated in Figure 5 , the uniaxial stress–strain response of the reinforcing steel was defined using an elastoplastic constitutive model with isotropic hardening.

The steel behavior was assumed to be linear elastic up to the yield stress f_y , followed by a plastic region characterized by strain hardening. After reaching the ultimate stress f_u , a descending branch was introduced to improve numerical stability and to realistically capture post-necking softening behavior in the finite element simulations.

The elastic modulus of steel was taken as $E_s = 210GPa$. The yield stress was defined as $f_y = 470MPa$, while the ultimate tensile stress was assumed as $f_u = 550MPa$. The ultimate strain corresponding to peak stress was defined as $\varepsilon_{su} = 12\%$and the rupture strain was specified to ensure stable convergence of the nonlinear analysis.

As shown in Figure 5, the adopted stress–strain relationship enables accurate simulation of yielding, strain hardening, and post-peak softening of the reinforcement bars under cyclic and monotonic loading conditions. This modeling approach ensures realistic interaction between steel and concrete and contributes to reliable prediction of structural response.

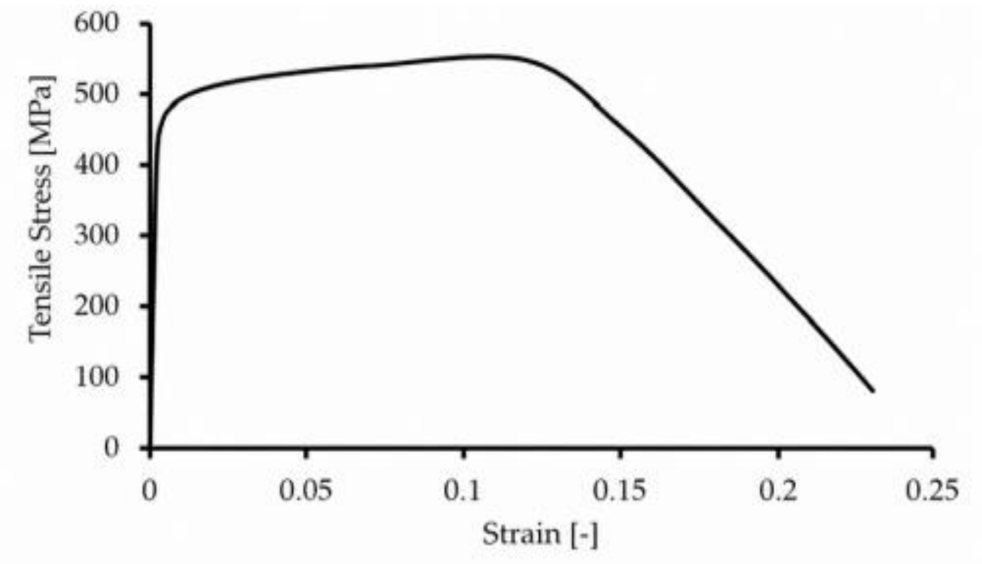


Figure 5 Tensile behavior of steel reinforcement for Frame [5]

3.5 Loading Protocol and Model Validation

Cyclic loading was applied through a displacement-controlled loading history, defined as a displacement–time waveform, as illustrated in Figure 6 . The imposed displacement history was introduced at the loading point to replicate the experimental testing protocol and accurately simulate the cyclic response of the reinforced concrete frame.

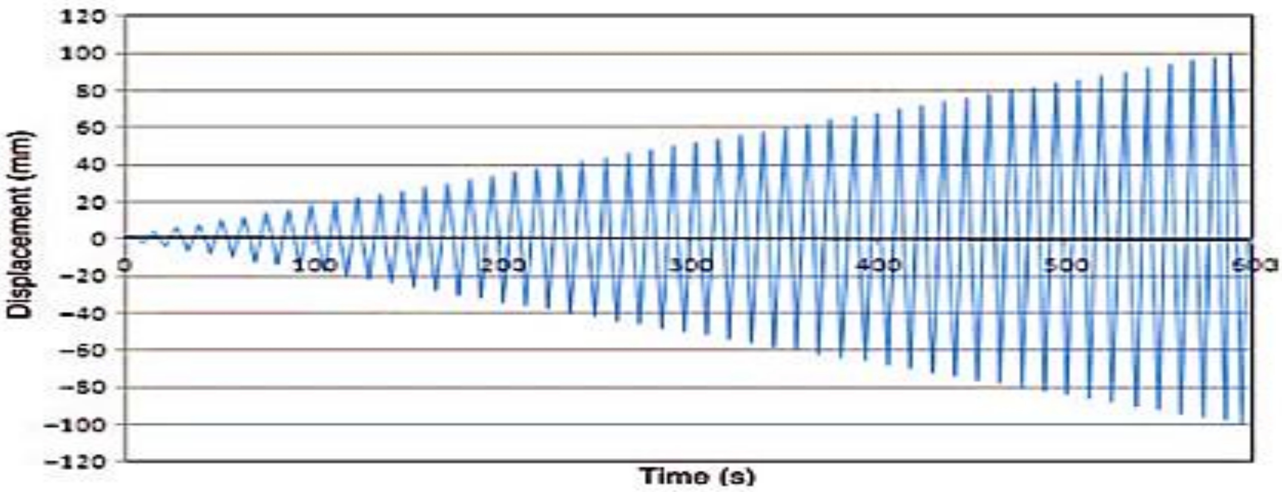


Figure 6 Loading protocol used in the test [36]

A mesh sensitivity study was conducted to determine the optimum mesh size capable of providing accurate numerical results with reasonable computational efficiency.

After the calibration process, the nonlinear finite element model was validated by comparing its backbone load–displacement response with the experimental results. The calibrated model, incorporating a dilation angle of 20°, stiffness recovery factor $wc = 0.2$, friction coefficient of 0.02, and a mesh size of 125 mm, produced the closest agreement with the experimental response. The comparison demonstrated that the numerical model accurately reproduced the overall structural behavior throughout the loading history, achieving approximately 95.12% agreement with the experimental peak lateral load.

As illustrated in Figure 7, the experimental specimen reached a peak lateral resistance of approximately 72 kN at a displacement of about 56 mm, whereas the finite element model predicted a peak load of approximately 71 kN at nearly the same displacement level. The difference in the predicted peak load was less than 5%, indicating excellent correlation between the numerical simulation and the experimental observations.

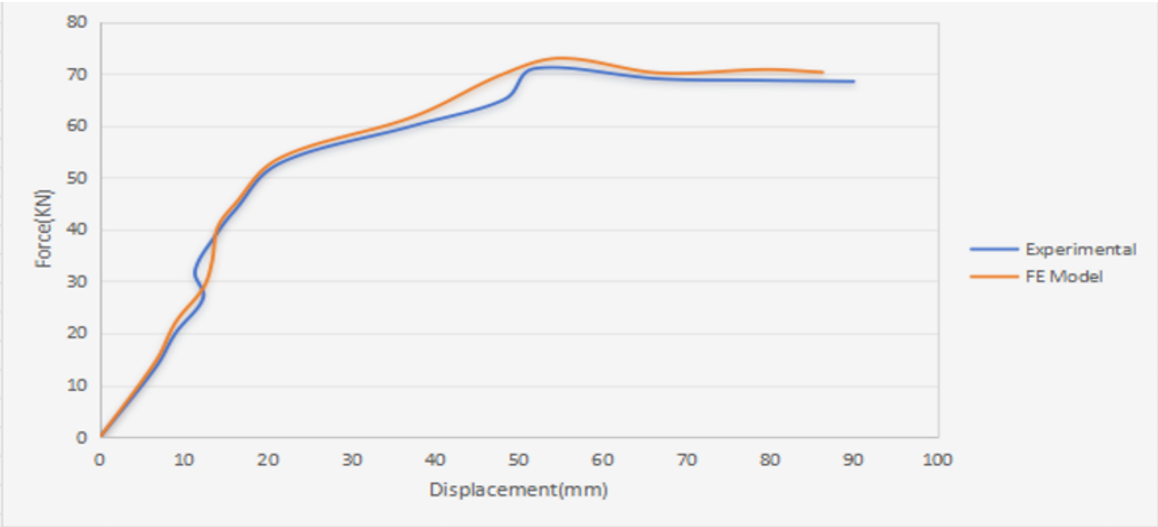


Figure 7 Experimental versus Numerical Backbone Response of the Validated Finite Element Model

Furthermore, the finite element model successfully captured the initial elastic stiffness, the onset of nonlinear behavior, the post-yield stiffness degradation, and the softening response observed experimentally. Minor discrepancies appeared only within the intermediate loading stage (approximately 10–20 mm displacement), where slight differences in local cracking and damage evolution resulted in small deviations between the two curves. Nevertheless, these differences remained insignificant and did not affect the overall prediction of the global structural response.

The close agreement between the experimental and numerical backbone curves confirms that the adopted constitutive models, material parameters, element discretization, and calibration procedure provide an accurate representation of the cyclic behavior of the reinforced concrete frame. Therefore, the validated finite element model was considered sufficiently reliable for the subsequent numerical investigation of the CFRP-, RC jacketing-, and UHPC-strengthened frames.

3.6 CFRP Strengthening Configuration

The initial strengthening scheme adopted in this study consisted of externally bonded carbon fiber-reinforced polymer (CFRP) sheets applied to the reinforced concrete frame. Two CFRP layers were utilized, each with a thickness of 0.1667 mm, to enhance the structural response under cyclic loading.

The CFRP was strategically distributed to target critical regions of expected damage. Full wrapping was applied at the beam–column joint to improve confinement and delay joint deterioration. In addition, the column base region was strengthened over a length of 50 cm to enhance its resistance against flexural and shear demands. For the beam, a U-shaped CFRP configuration was implemented at the mid-span over a length of 70 cm, corresponding to the region of maximum bending moment, as illustrated in Figure 8.

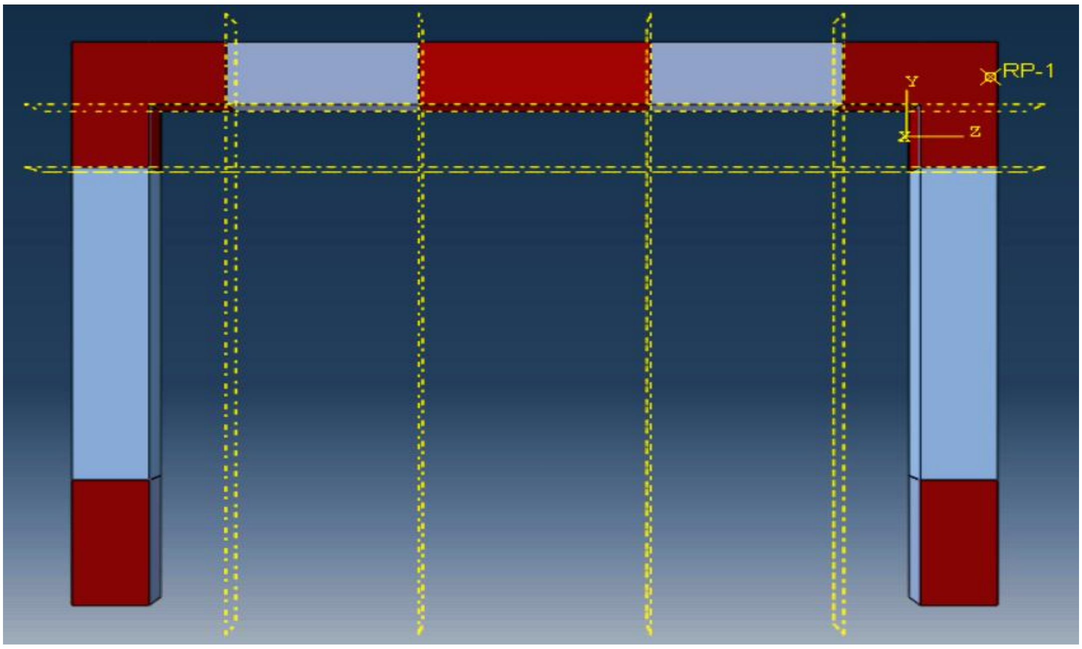


Figure 8 CFRP Strengthening Configuration and Sheet Distribution

A perfect bond condition between CFRP and concrete was assumed using a tie constraint, ensuring full strain compatibility and efficient stress transfer across the interface. The mechanical properties of the CFRP material were adopted from [9] and are summarized in Table 5.

Table 5 CFRP Properties .

Type	Thickness (mm)	Modulus of elasticity (GPa)	Tensile strength (MPa)
CFRP	0.1667	240	4340

3.7 Concrete Jacketing

A concrete jacketing technique was implemented to strengthen the columns, increasing the cross-section from 250 × 250 mm to 350 × 350 mm. The jacket was reinforced with 6Ø12 longitudinal bars and Ø10 stirrups spaced at 100 mm, and was applied up to the beam – column interface . The material properties of the concrete and steel were assumed to be the same as those used in the control (un-retrofitted) model to ensure consistency in comparison. The configuration is shown in Figure 9.

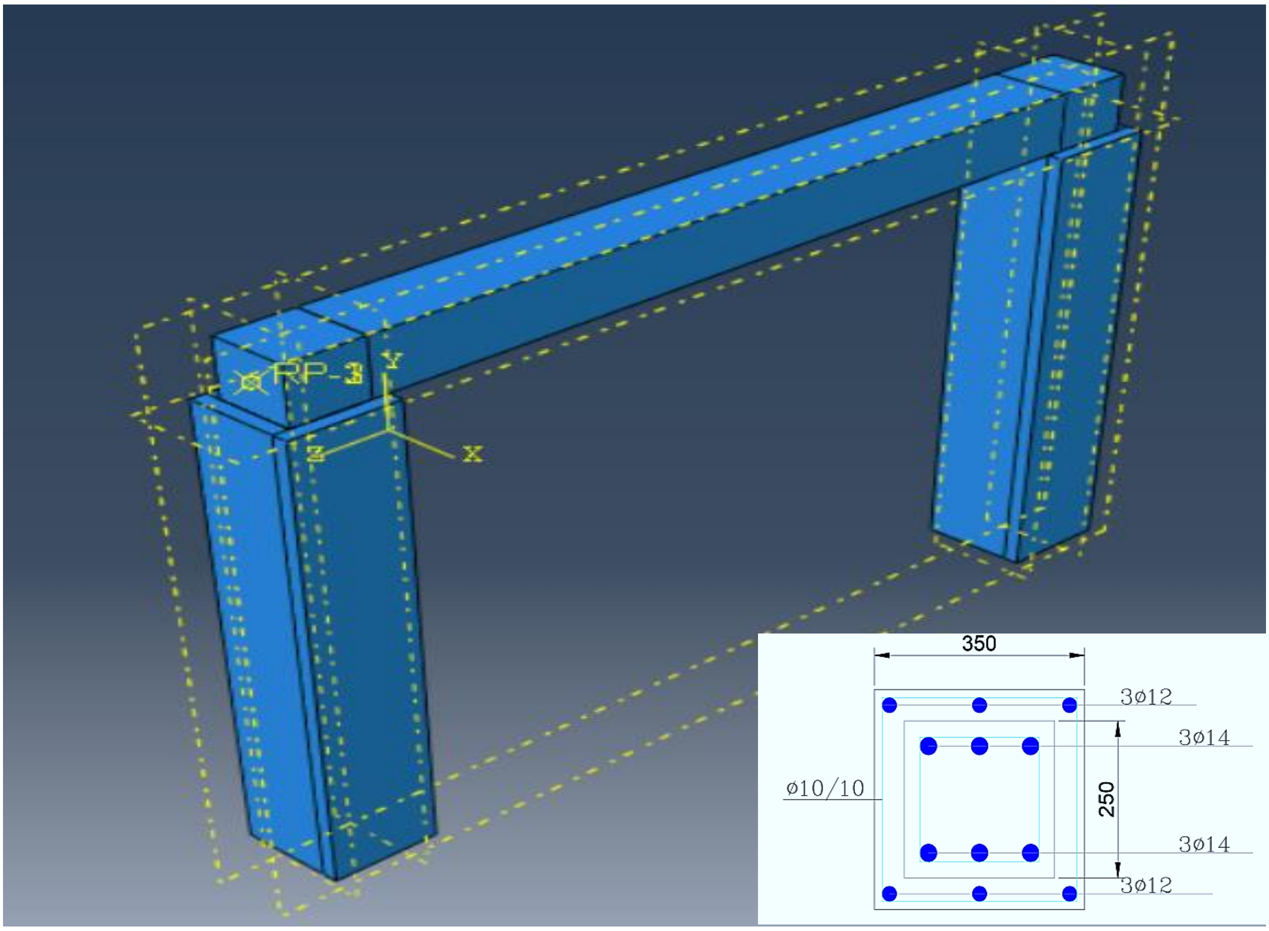


Figure 9 Concrete Jacketing Configuration and Reinforcement Details of the Strengthened RC Frame

3.8 UHPC Strengthening Modeling

In this study, a finite element model was developed to evaluate the effectiveness of ultra-high-performance concrete (UHPC) as a strengthening technique for reinforced concrete (RC) columns. A 20 mm thick UHPC layer was applied around the full column height up to the beam–column joint region, as illustrated in Figure 10. This configuration enhances confinement and contributes to improving the structural response under cyclic loading conditions. The selected thickness was adopted to achieve an optimal balance between structural enhancement and numerical stability.

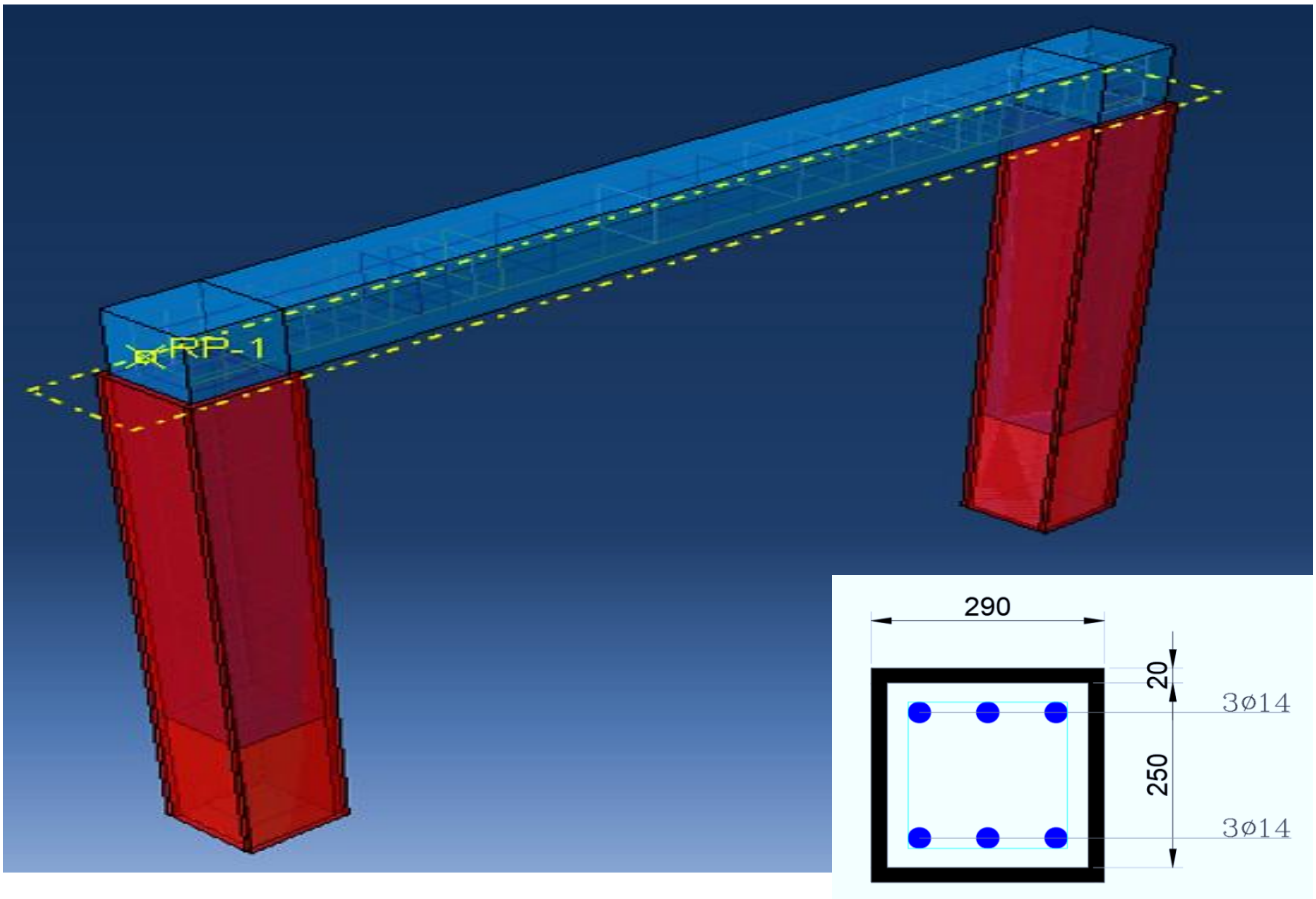


Figure 10 UHPC Jacketing Configuration and Column Cross-Section

The UHPC material properties were defined based on values reported in the literature [38], where the elastic modulus, compressive strength, and tensile strength were taken as $E = 46GPa$, $fc' = 170MPa$, and $ft = 7.3MPa$, respectively, as presented in Figure 11.

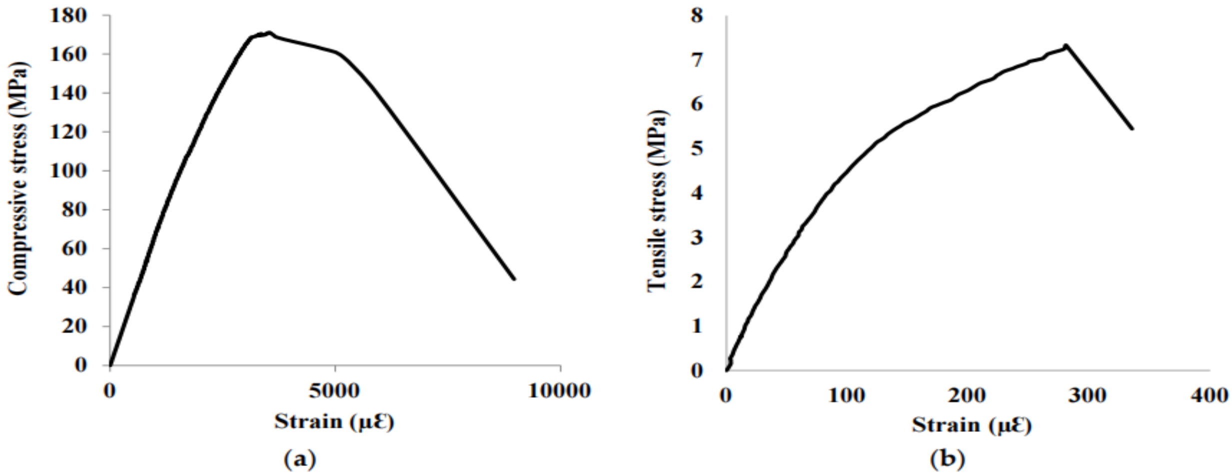


Figure 11 Stress-strain curve for UHPC in (a) compression (b) direct tension [38]

The nonlinear behavior of UHPC was simulated using the Concrete Damage Plasticity (CDP) model in ABAQUS. The adopted CDP parameters are summarized in Table 6.

Table 6 Input parameter values for UHPC to define the CDPM .

Parameter	Symbol	Value
Density (Kg/m^3)	γ	2500
Dilation Angle	Φ	20°
Eccentricity	ε	0.1
Biaxial/Uniaxial Strength Ratio	fb'/fc'	1.175
Deviatoric Shape Factor	K_c	0.6555
Viscosity Parameter	M	0.001

3.9 Chapter Summary

This chapter presented the development and calibration of the finite element model adopted for simulating the cyclic behavior of reinforced concrete frames. The numerical model demonstrated close agreement with the experimental response in terms of load–displacement behavior, stiffness degradation, and damage propagation. Following model validation, different strengthening techniques including CFRP strengthening, RC jacketing, and UHPC strengthening were implemented to evaluate their effectiveness in enhancing the seismic performance of the RC frame.

The validated numerical model provides a reliable basis for the comparative assessment of the proposed seismic strengthening techniques presented in the subsequent chapter.

Chapter 4: Results and Discussion

4.1 Introduction

This chapter presents the numerical results obtained from the finite element analysis conducted using ABAQUS. A reinforced concrete (RC) frame experimentally tested in the literature [36] was modeled and validated, where the developed numerical model achieved approximately 95.12% agreement with the experimental response.

Following the validation process, several strengthening techniques, including CFRP strengthening, RC jacketing, and UHPC strengthening, were implemented to evaluate their effectiveness in improving the seismic performance of the RC frame under cyclic loading conditions representing earthquake actions.

4.2 Calibration and Validation of the Finite Element Model

To ensure the reliability of the developed finite element model, a comprehensive calibration procedure was conducted by comparing the numerical response with the experimental results reported in the literature [36]. Several numerical parameters, including mesh size, dilation angle, stiffness recovery coefficients, and contact interaction properties, were systematically investigated to identify the combination that provided the closest agreement with the experimental cyclic response.

The calibration results indicated that a mesh size of **125 mm**, a dilation angle of **20°**, a compression stiffness recovery factor of **0.2**, and a friction coefficient of **0.02** produced the best correlation with the experimental observations. Using these parameters, the developed numerical model achieved approximately **95.12%** agreement with the experimentally measured peak lateral load while accurately reproducing the overall backbone response.

This level of agreement indicates that the adopted constitutive models and calibration strategy were capable of reproducing the global structural behavior with satisfactory accuracy.

The influence of mesh size and dilation angle on the numerical response is illustrated in Figures 12 and 13, respectively. The results indicate that coarse meshes underestimated the initial stiffness and peak lateral resistance, whereas finer meshes resulted in only minor improvements in prediction accuracy while considerably increasing the computational cost. Therefore, a mesh size of 125 mm was selected as the optimum compromise between numerical accuracy and computational efficiency.

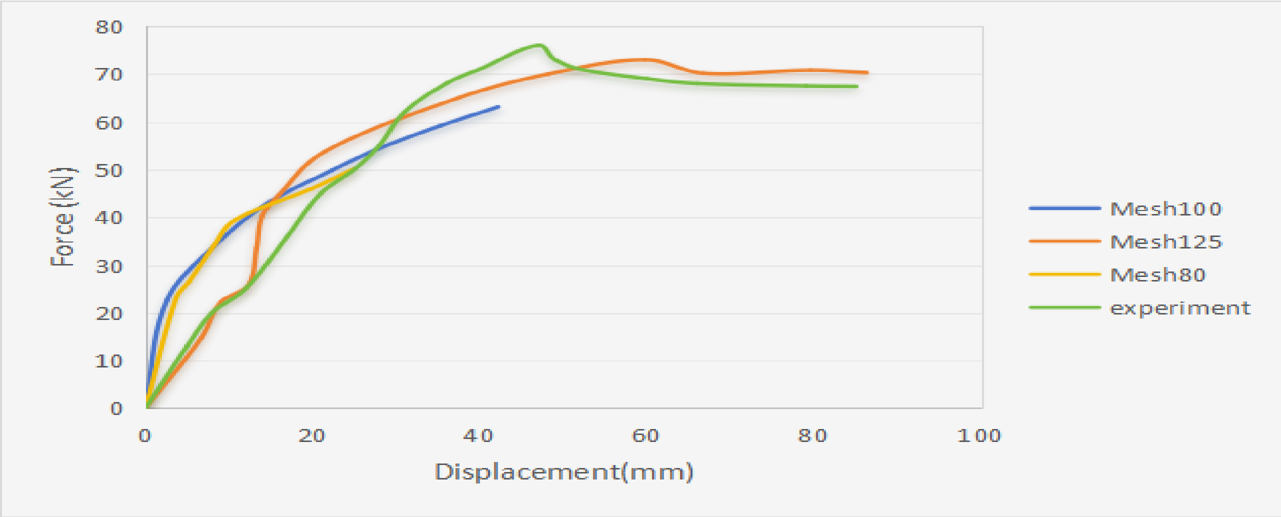


Figure 12 Effect of Mesh Size Calibration on the Backbone Response of the RC Frame under Cyclic Loading

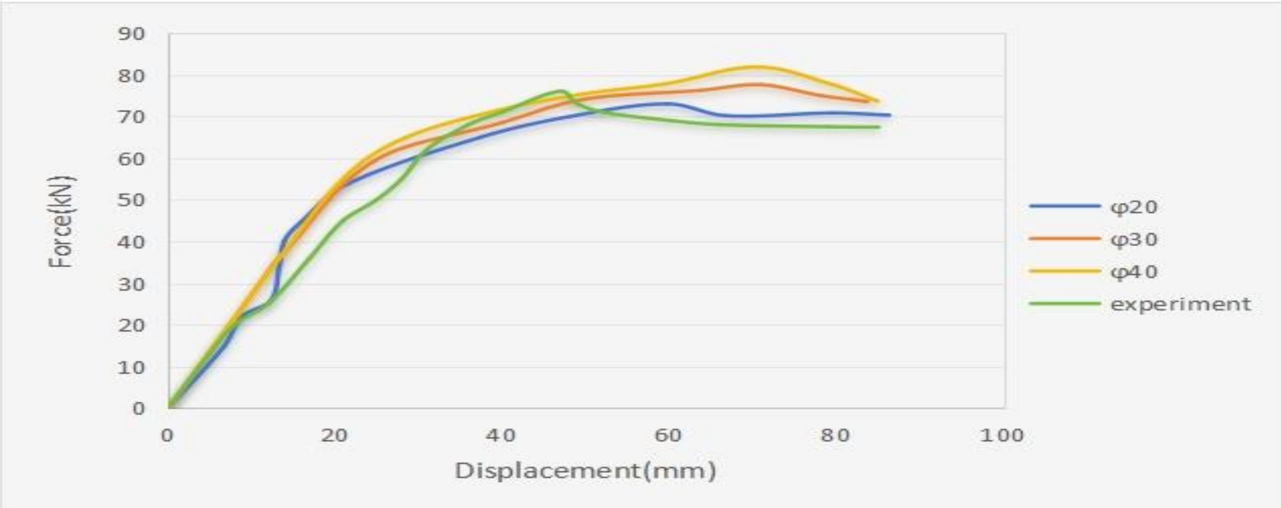
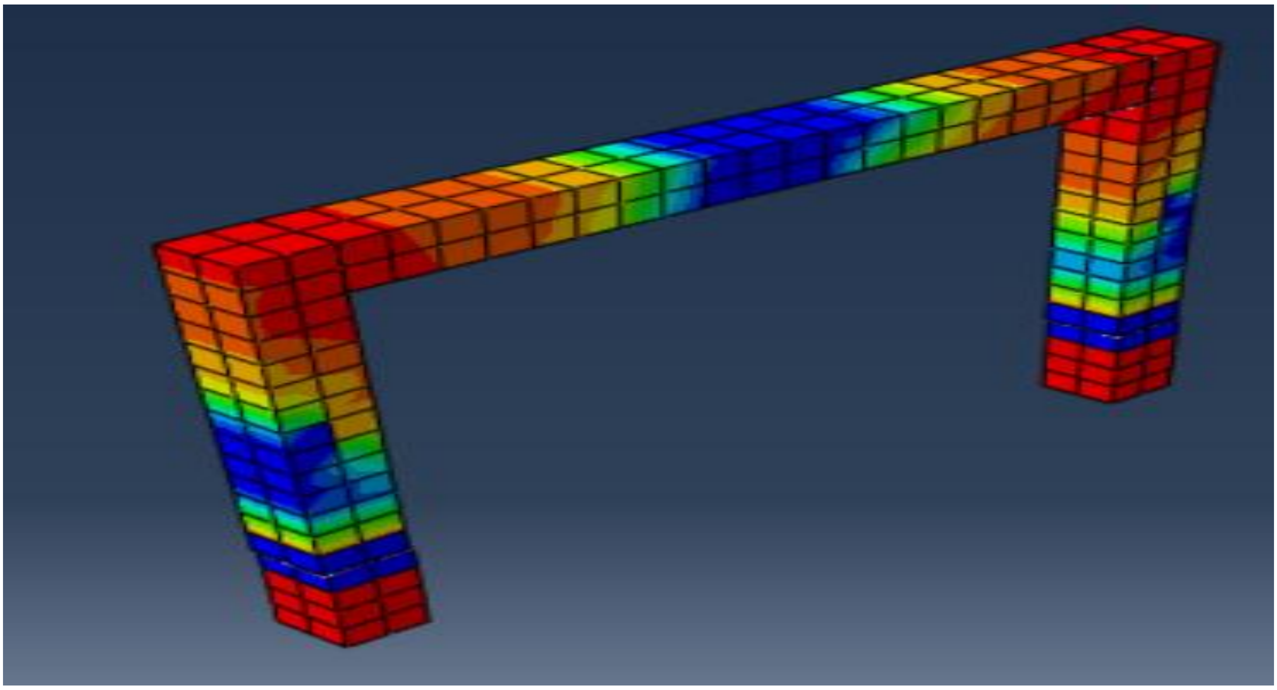


Figure 13 Influence of Dilation Angle on the Numerical Backbone Curve and Seismic Response Calibration

Furthermore, a comparison between the experimental observations and the numerical predictions demonstrated good agreement regarding crack initiation, damage localization, and overall failure mechanism. In both cases, damage was primarily concentrated at the beam–column joints and column bases, which are recognized as the most critical regions subjected to cyclic loading. The similarity between the experimental crack pattern and the numerical damage contours confirms the capability of the adopted CDP model to accurately reproduce the observed failure mode. The comparison is presented in Figure 14.

(a)



(b)

Figure 14 Comparison of Experimental and Numerical Damage Patterns in the RC Frame under Cyclic Loading: (a) Experimental Crack Distribution and Failure Mechanism [36]. (b) Finite Element Damage Contours and Crack Localization using ABAQUS CDP Model.

These observations are consistent with previous numerical investigations. Shamsi and Sümer [5] demonstrated that carefully calibrated ABAQUS models employing the Concrete Damage Plasticity (CDP) model accurately reproduce the cyclic response of reinforced concrete frames. Likewise, Xie et al. [6] reported that appropriate calibration of nonlinear material parameters enables reliable prediction of stiffness degradation, crack propagation, and collapse mechanisms under earthquake loading.

Accordingly, the validated finite element model was adopted as the baseline numerical model for all subsequent strengthening simulations. The calibrated model provided a reliable analytical platform for evaluating and comparing the seismic performance of CFRP-, RC jacketing-, and UHPC-strengthened reinforced concrete frames under identical cyclic loading conditions.

4.3 Seismic Performance of the CFRP-Strengthened Frame

The application of CFRP sheets significantly improved the seismic performance of the reinforced concrete frame subjected to cyclic loading. The numerical results indicated that the maximum lateral load increased from **74.00 kN** for the control frame to **109.65 kN** after strengthening, representing an increase of approximately **48.18%**. This substantial improvement demonstrates the effectiveness of externally bonded CFRP sheets in enhancing the lateral load-carrying capacity of existing reinforced concrete frames.

The observed increase in strength can be primarily attributed to the confinement effect provided by the CFRP sheets around the beam–column joint and column base regions. The CFRP wrapping enhanced the confinement of concrete, delayed tensile crack propagation, and improved stress transfer between the concrete and reinforcing steel. Consequently, premature concrete deterioration was reduced, allowing the frame to sustain higher lateral loads before reaching its ultimate capacity.

In addition to the increase in strength, the CFRP strengthening technique significantly improved the deformation capacity of the frame. The numerical analysis showed that the ductility increased by approximately **32%**, while the initial stiffness increased from **5.00 kN/mm** to **6.03 kN/mm**. The higher initial stiffness reduced lateral deformation during the early loading stages, whereas the increased ductility enabled the structure to undergo larger inelastic deformations while maintaining stable structural performance.

The hysteretic response presented in Figure 15 demonstrates fuller and more stable hysteresis loops compared with those of the control frame, indicating improved cyclic stability and enhanced energy dissipation capacity. Furthermore, the reduced pinching effect observed during successive loading cycles reflects the ability of the CFRP sheets to maintain the integrity of the critical regions and delay the degradation of stiffness under repeated cyclic loading.

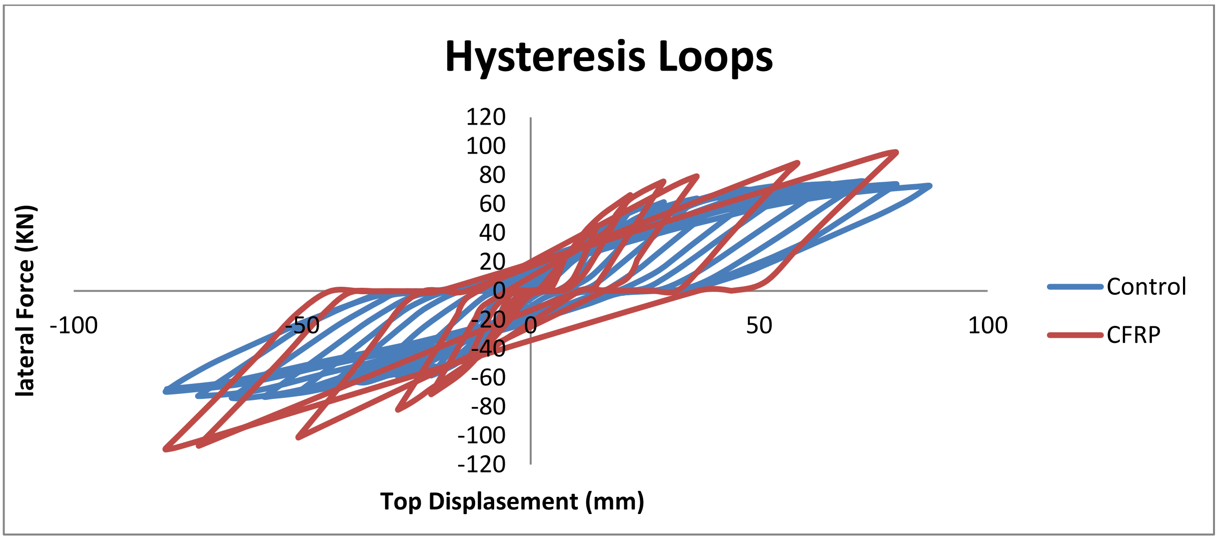


Figure 15 Hysteretic Response of the CFRP-Strengthened RC Frame under Cyclic Loading

The damage contours obtained from the finite element analysis further confirmed the beneficial effect of CFRP strengthening. Compared with the control frame, damage became less concentrated within the beam–column joint and column base regions, while crack propagation was significantly reduced. This behavior indicates that the CFRP sheets effectively redistributed stresses away from critical locations, thereby delaying damage accumulation and improving the overall structural integrity of the frame under cyclic loading.

The numerical findings obtained in the present study are consistent with the experimental and numerical investigations reported by Wang et al. [9], Katsumata et al. [12], Zafra and Kawashima [13], and the recommendations provided in ACI 440.2R-17 [28]. These studies similarly concluded that externally bonded CFRP systems effectively increase lateral strength, improve stiffness and ductility, enhance energy dissipation capacity, and delay crack propagation in reinforced concrete members subjected to earthquake-type loading.

Overall, the results demonstrate that CFRP strengthening provides an efficient seismic retrofit solution for existing reinforced concrete frames by significantly improving strength, stiffness, ductility, and cyclic stability while requiring only minimal additional weight and negligible changes to the original structural dimensions.

4.4 Seismic Performance of the RC-Jacketed Frame

The application of reinforced concrete (RC) jacketing significantly enhanced the lateral load-carrying capacity of the reinforced concrete frame under cyclic loading. The numerical analysis indicated that the maximum lateral load increased from 74.00 kN for the control frame to approximately 100.00 kN after strengthening, representing an increase of approximately 35%. This improvement confirms the effectiveness of RC jacketing in increasing the strength and load resistance of existing reinforced concrete structures.

The increase in lateral strength is primarily attributed to the enlargement of the column cross-sectional area and the addition of longitudinal and transverse reinforcement provided by the concrete jacket. These modifications enhanced the flexural and shear capacities of the strengthened columns while improving the confinement of the concrete core. As a result, the strengthened frame exhibited higher resistance against lateral seismic loads and delayed the onset of structural damage.

The RC jacketing technique also increased the initial stiffness of the structural system and reduced the rate of stiffness degradation throughout the loading history. The additional concrete section and reinforcement increased the overall rigidity of the frame, thereby reducing lateral displacements during the early stages of cyclic loading. However, the increase in stiffness was accompanied by a reduction in structural ductility. The strengthened frame reached its peak resistance at smaller deformation levels than the control frame, indicating a more brittle global response compared with the CFRP-strengthened model.

Moreover, the increased column stiffness modified the internal force distribution within the frame, resulting in the earlier formation of plastic hinges in adjacent beam regions. This behavior is consistent with the strong column–weak beam design philosophy, in which the strengthened columns remain relatively elastic while inelastic deformations are intentionally transferred to the beams. Consequently, the failure mechanism shifted away from the strengthened columns toward the beam elements, contributing to a more desirable global collapse mechanism.

The hysteretic response presented in Figure 16 demonstrates that the RC-jacketed frame sustained higher lateral loads than the control frame while maintaining relatively stable hysteresis loops throughout the loading cycles. The larger enclosed hysteresis loops indicate an improvement in energy dissipation capacity; however, the response also exhibited slightly faster strength degradation during large displacement cycles compared with the CFRP-strengthened frame, reflecting the lower deformation capacity associated with the increased structural stiffness.

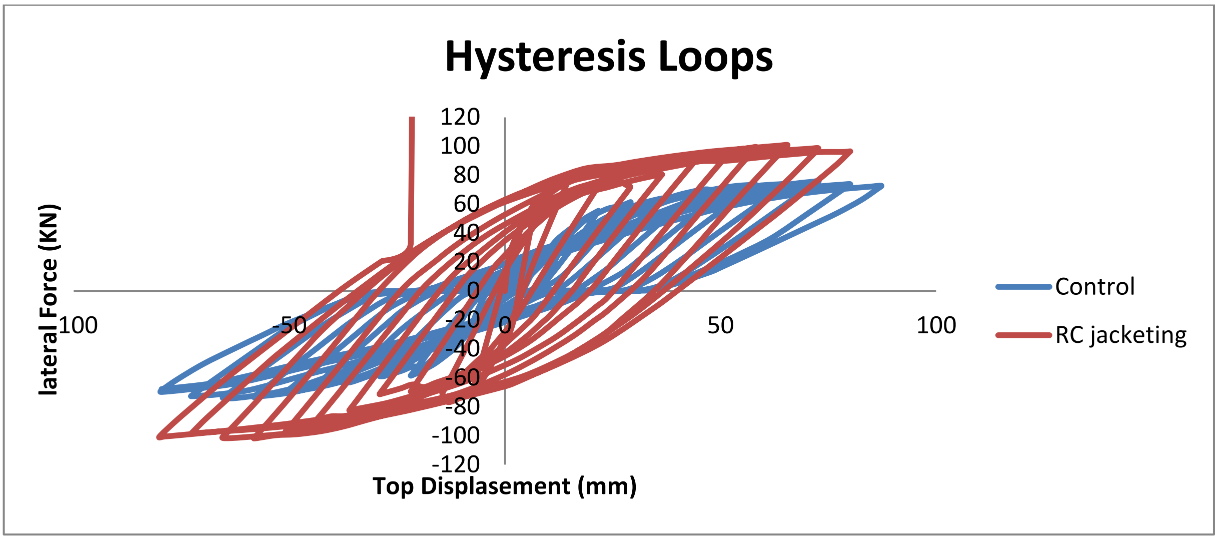


Figure 16 Hysteretic Response of the RC Jacketed RC Frame under Cyclic Loading

The numerical damage patterns further demonstrated that RC jacketing effectively reduced damage concentration at the column bases and beam–column joints by increasing the local strength and confinement of these critical regions. Nevertheless, localized damage gradually developed in adjacent beam sections due to the redistribution of internal forces, confirming the shift in the plastic hinge formation mechanism after strengthening.

The numerical observations obtained in this study are consistent with the experimental investigations reported by Nechevska-Cvetanovska et al. [10], Elbetar and Issa [11], and Bousias et al. [23], who similarly reported that RC jacketing substantially increases lateral strength and structural stiffness while modifying the failure mechanism and reducing the overall ductility of reinforced concrete frames subjected to seismic loading.

Overall, RC jacketing proved to be an effective seismic strengthening technique for increasing the load-carrying capacity and stiffness of reinforced concrete frames. However, the accompanying reduction in ductility highlights the importance of carefully considering the balance between strength enhancement and deformation capacity during the design of seismic retrofit schemes.

4.5 Effect of UHPC Strengthening

The Ultra-High Performance Concrete (UHPC) strengthening technique exhibited the most significant improvement in the seismic performance of the reinforced concrete frame under cyclic loading among all the investigated strengthening methods. The numerical analysis showed that the maximum lateral load increased from **74.00 kN** for the control frame to **139.50 kN** after strengthening, corresponding to an increase of approximately **88.5%**. This substantial enhancement confirms the superior strengthening capability of UHPC compared with the conventional retrofit techniques investigated in this study.

The remarkable increase in strength can be primarily attributed to the exceptional mechanical properties of UHPC, including its very high compressive strength, enhanced tensile resistance, dense microstructure, and excellent bond characteristics with the existing concrete substrate. The UHPC jacket effectively increased both the flexural and shear capacities of the critical structural regions while providing additional confinement to the concrete core. Consequently, stress concentrations were significantly reduced, allowing the frame to sustain considerably higher lateral loads before reaching its ultimate capacity.

In addition to the strength enhancement, the UHPC strengthening technique produced the greatest improvement in deformation capacity among all strengthening schemes. The numerical results indicated that the ductility increased by approximately **44.73%**, while the initial stiffness increased from **5.00 kN/mm** to **7.01 kN/mm**. This simultaneous improvement in both stiffness and ductility demonstrates the ability of UHPC to increase structural rigidity without significantly compromising the deformation capacity of the frame, thereby achieving a more balanced seismic performance.

The hysteretic response presented in Figure 17 exhibits wider, fuller, and more stable hysteresis loops compared with both the control frame and the other strengthened models. The larger enclosed loop area indicates a substantial increase in energy dissipation capacity, while the reduced pinching effect reflects improved cyclic stability and slower stiffness degradation during repeated loading cycles. These characteristics demonstrate that the UHPC strengthening system effectively maintained the structural integrity of the frame throughout the loading history.

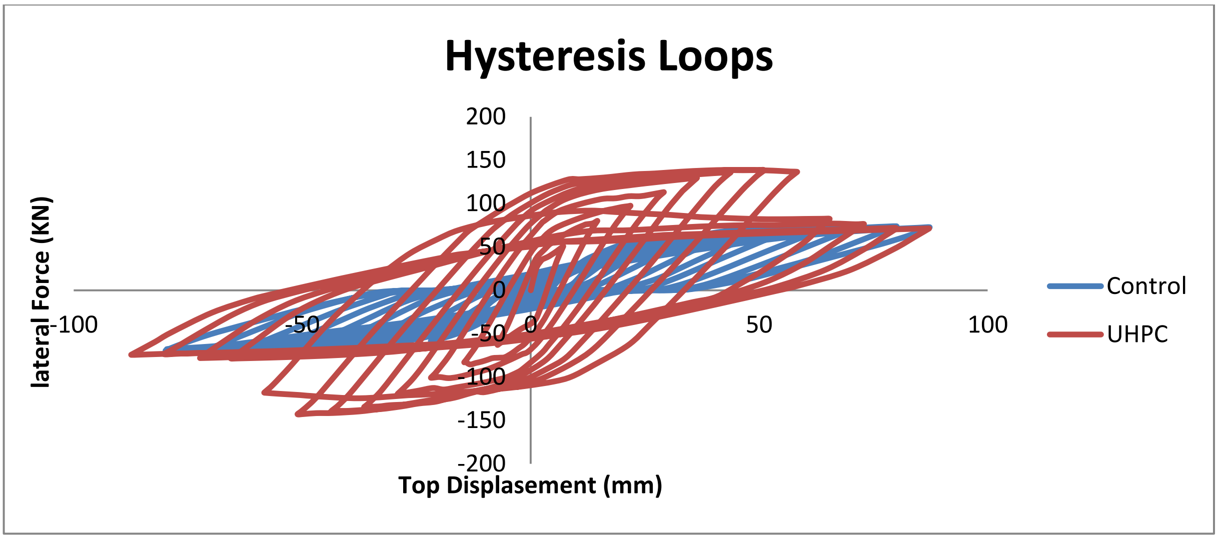


Figure 17 Hysteretic Response of the UHPC-Strengthened RC Frame under Cyclic Loading

The finite element damage contours further confirmed the effectiveness of UHPC strengthening. Compared with the control frame, damage was significantly reduced within the beam–column joints and column base regions, where seismic damage is typically concentrated. The high stiffness and confinement provided by the UHPC layer improved stress redistribution, delayed crack initiation, and substantially limited crack propagation throughout the loading process.

Although localized crushing damage was observed near the beam–column joint region, as illustrated in Figure 19(d), this behavior was confined to a relatively small area subjected to severe stress concentration. The occurrence of localized damage can be attributed to the considerable increase in local stiffness introduced by the UHPC jacket, which altered the internal stress distribution within the joint region. Nevertheless, this localized failure did not compromise the overall structural stability, and the frame continued to exhibit stable load-carrying capacity and satisfactory cyclic performance throughout the analysis.

The numerical observations obtained in this study are in good agreement with previous experimental investigations reported by Wille et al. [14], Zhang et al. [15], Shao et al. [16], Hung and Hsiao [18], Graybeal [32,33], Yoo and Banthia [34], and the recommendations presented in ACI 239R-18 [35]. These studies consistently demonstrated that UHPC strengthening provides superior confinement, excellent crack control, high stiffness retention, and remarkable improvements in strength, ductility, and energy dissipation under cyclic loading.

Overall, the UHPC strengthening technique proved to be the most effective retrofit strategy investigated in the present study. It provided the highest increase in lateral strength, the greatest improvement in ductility and stiffness, superior energy dissipation capacity, and the most effective control of damage development, making UHPC a highly promising solution for the seismic rehabilitation of existing reinforced concrete frames.

4.6 Comparative Performance of Strengthening Techniques

This section presents a comprehensive comparison between the strengthening techniques investigated in this study, namely CFRP strengthening, RC jacketing, and UHPC jacketing, based on the nonlinear finite element results obtained under cyclic loading conditions. The comparison was conducted in terms of lateral load capacity, stiffness, ductility, energy dissipation capacity, hysteretic response, and failure mechanisms.

The backbone curves of the control and strengthened frames are illustrated in Figure 18. The results clearly demonstrate that all strengthening techniques improved the seismic performance of the RC frame compared with the control model. However, the degree of enhancement varied according to the strengthening system and its contribution to stiffness, confinement, and crack control mechanisms.

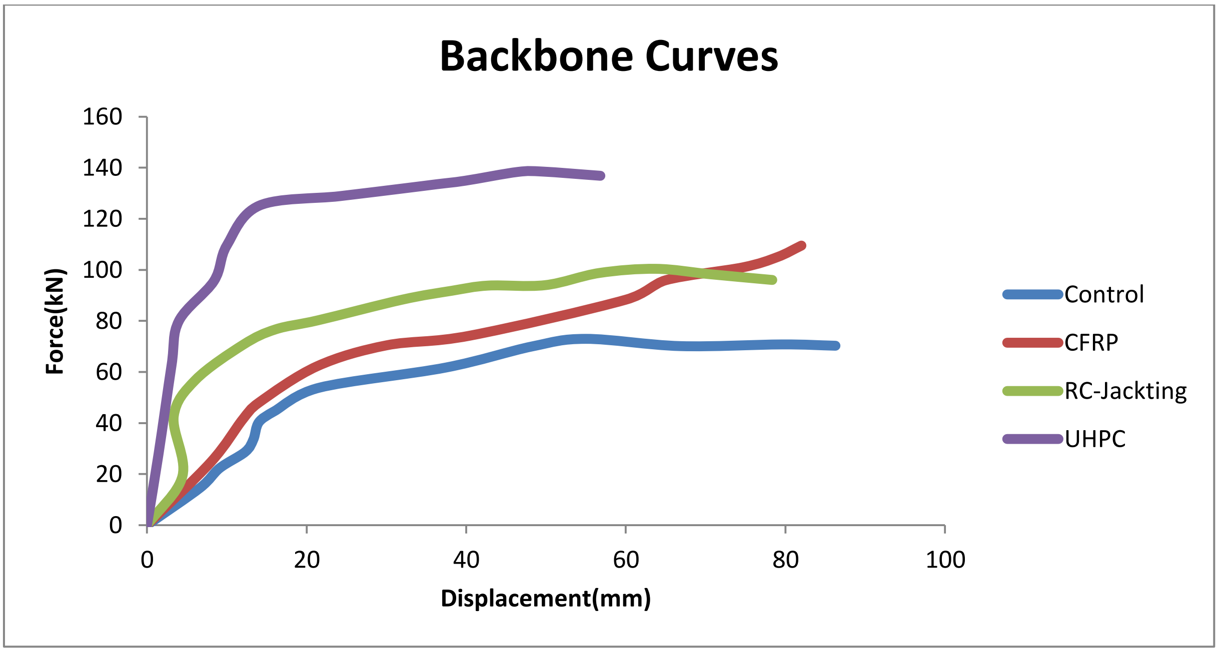


Figure 18 Comparison of Backbone Curves and Seismic Response Enhancement for Control and Strengthened RC Frames Under Cyclic Loading

Among all investigated techniques, the UHPC-strengthened frame exhibited the best overall structural performance. The maximum lateral load capacity increased from 74 kN for the control frame to 139.5 kN, corresponding to an increase of approximately 88.5%. In addition, the initial stiffness increased from 5 kN/mm to 7.01 kN/mm, while the ductility improved by approximately 44.73%. The UHPC model also demonstrated the most stable hysteretic response and the highest energy dissipation capacity, as evidenced by the wider and more stable hysteresis loops shown in Figure 19. The superior performance of UHPC can be attributed to its high compressive strength, enhanced tensile resistance, and improved confinement effect, which delayed crack propagation and reduced stiffness degradation during cyclic loading.

The CFRP-strengthened frame also showed significant enhancement in structural behavior. The lateral load capacity increased to 109.65 kN, representing an increase of approximately 48.18% compared with the control frame. Moreover, the stiffness increased from 5 kN/mm to 6.03 kN/mm, while the ductility improved by approximately 32%. The hysteretic response indicated improved cyclic stability and enhanced energy dissipation due to the confinement effect provided by the CFRP sheets. The strengthening system effectively reduced crack concentration in the beam–column joint region and delayed the formation of severe damage mechanisms.

In contrast, the RC-jacketed frame achieved moderate improvement in seismic performance. The strengthening technique increased the maximum lateral load capacity to approximately 100 kN, corresponding to an increase of about 35%. In addition, the initial stiffness increased to 6.06 kN/mm, while the ductility improved by approximately 20% compared with the control frame. This enhancement can be attributed to the increased confinement and the more uniform stress distribution over the enlarged column cross-section. However, the higher stiffness of the strengthened frame promoted earlier plastic hinge formation and resulted in a stronger column – weaker beam response mechanism under cyclic loading conditions.

The comparison of failure modes and crack propagation patterns for the control and strengthened frames is presented in Figure 19. The control frame exhibited severe cracking and concentrated damage at the beam–column joints and column base regions, indicating significant stiffness degradation and plastic hinge formation. The CFRP-strengthened model showed reduced crack propagation and improved confinement at critical regions, while the RC-jacketed frame exhibited reduced local damage but more concentrated stiffness-related failure behavior. On the other hand, the UHPC-strengthened frame demonstrated the most uniform damage distribution and the least crack concentration among all investigated models, confirming its superior confinement efficiency and enhanced cyclic performance.

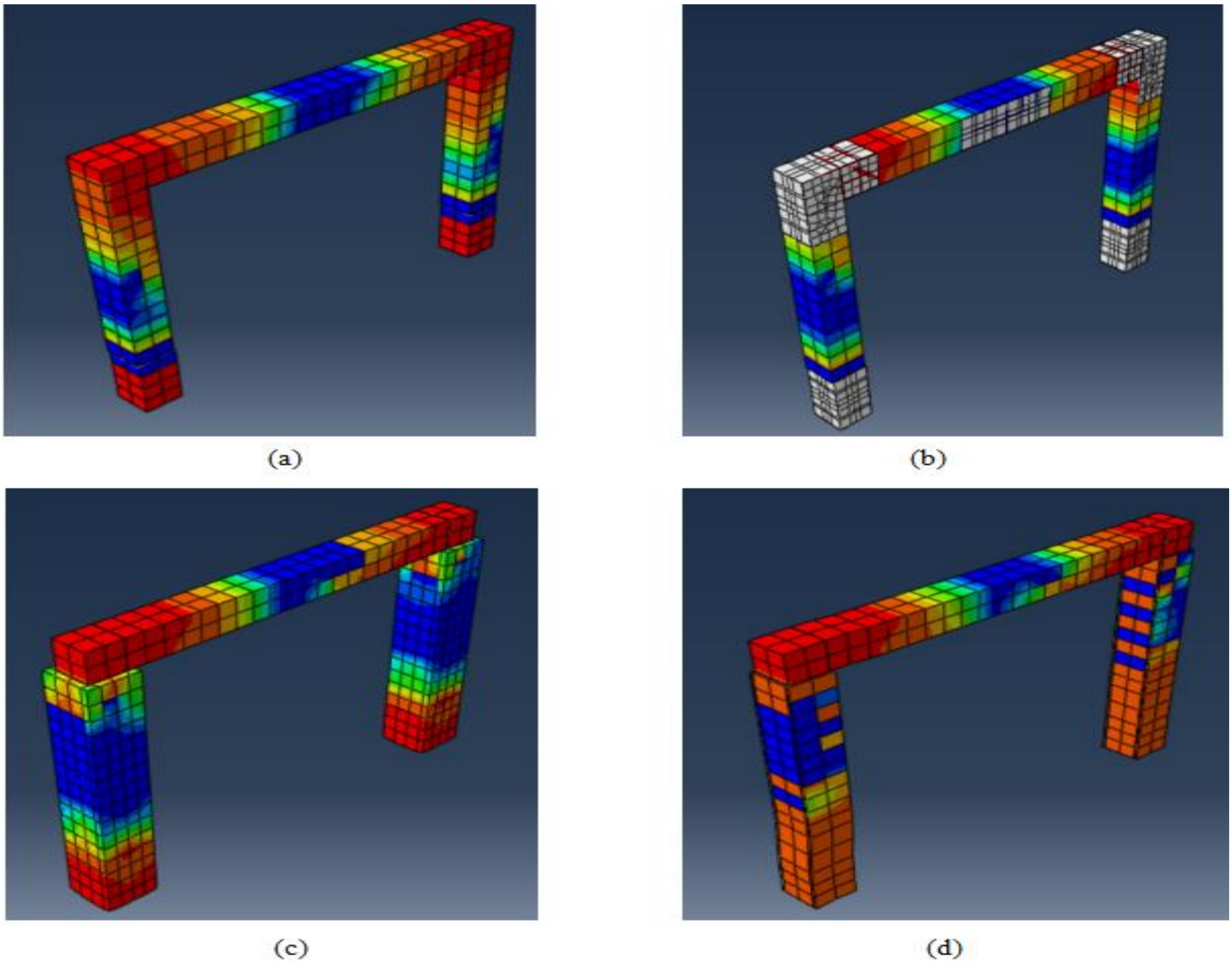


Figure 19 Comparative Crack Propagation and Failure Mechanisms of **(a)** Control, **(b)** CFRP-, **(c)** RC Jacket, **(d)**UHPC-Strengthened RC Frames.

The cumulative dissipated energy obtained from the hysteretic response was also evaluated to assess the seismic efficiency of each strengthening technique. The results indicated that the UHPC-strengthened frame achieved the highest energy dissipation capacity, followed by the RC-jacketed frame and the CFRP-strengthened model.The enhanced energy absorption capability of the UHPC system is attributed to its superior confinement efficiency, stable hysteretic response, and delayed stiffness degradation under cyclic loading.

The key seismic performance indicators obtained from the numerical analysis are summarized in Table 7.

Table 7 Comparative Seismic Performance of Strengthening Techniques

Model	Max Lateral Load (kN)	Increase in Strength (%)	Initial Stiffness (kN/mm)	Ductility Increase (%)	Dissipated Energy (kN·mm)	Failure Characteristics
Control Frame	74.0	—	5.00	—	29565.98	Severe cracking at joints and column bases
CFRP Strengthening	109.65	48.18	6.03	32	61762.32	Reduced joint cracking and delayed damage propagation
RC Jacketing	100.0	35.0	6.06	20	89066.11	Increased stiffness with earlier plastic hinge formation
UHPC Strengthening	139.5	88.5	7.01	44.73	102624.6	Reduced crack concentration with localized damage at the beam–column joint

Overall, the results confirm that UHPC strengthening provided the most efficient and effective seismic retrofitting strategy among all investigated techniques. The UHPC system achieved the highest enhancement in strength, stiffness, ductility, and energy dissipation simultaneously, resulting in superior cyclic performance and improved structural stability under seismic loading conditions.

4.7 Summary of Numerical Findings

The principal findings obtained from the nonlinear finite element analysis can be summarized as follows:

- UHPC strengthening exhibited the best overall seismic performance, providing the highest increase in lateral load capacity (approximately 88.5%), together with the greatest improvements in stiffness, ductility, and energy dissipation.

- CFRP strengthening effectively enhanced the structural ductility and cyclic stability while significantly increasing the lateral load capacity and reducing damage concentration at the beam–column joints and column bases.

- RC jacketing substantially increased the lateral strength and initial stiffness of the reinforced concrete frame. However, the increased rigidity resulted in a reduction in global ductility and altered the plastic hinge formation mechanism.

- The calibrated finite element model accurately reproduced the experimental structural response, achieving approximately 95.12% agreement in peak lateral load and demonstrating good correlation in backbone response and damage distribution.

- The comparison between the three strengthening techniques demonstrated that UHPC provides the most balanced seismic retrofit solution, combining superior strength, stiffness, ductility, energy dissipation capacity, and effective damage control under cyclic loading.

Chapter 5: Conclusions and Future Work

5.1 Conclusions

This study presented a comprehensive nonlinear finite element investigation of the seismic behavior of reinforced concrete (RC) frames strengthened using Carbon Fiber Reinforced Polymer (CFRP), Reinforced Concrete (RC) Jacketing, and Ultra-High Performance Concrete (UHPC). A three-dimensional finite element model was developed in ABAQUS and validated against published experimental results. The calibrated model successfully reproduced the cyclic structural response, including load–displacement behavior, stiffness degradation, crack development, and failure mechanisms, achieving approximately 95.12% agreement with the experimental peak lateral load.

Following model validation, three strengthening techniques were implemented and evaluated under identical cyclic loading conditions to enable a direct comparison of their effectiveness. Based on the numerical investigation, the following conclusions can be drawn:

1. The developed finite element model based on the Concrete Damage Plasticity (CDP) formulation proved capable of accurately predicting the nonlinear cyclic response of reinforced concrete frames, confirming the suitability of ABAQUS for seismic assessment and strengthening studies.

2. The adopted calibration strategy demonstrated that a 125 mm mesh size, 20° dilation angle, compression stiffness recovery factor of 0.2, and friction coefficient of 0.02 provided the closest agreement with the experimental observations while maintaining computational efficiency.

3. CFRP strengthening considerably improved the seismic performance of the reinforced concrete frame. The lateral load capacity increased from 74.00 kN to 109.65 kN, representing an improvement of approximately 48.18%, while the ductility increased by nearly 32%. The strengthening system also delayed crack propagation and reduced damage concentration within the beam–column joint region.

4. RC jacketing significantly enhanced the lateral load capacity and structural stiffness, increasing the maximum lateral resistance to approximately 100 kN (35% improvement). However, the increased rigidity reduced the global ductility of the frame and promoted earlier plastic hinge formation.

5. UHPC strengthening exhibited the best overall structural performance among all investigated retrofit techniques. The maximum lateral load increased to 139.50 kN, corresponding to an enhancement of approximately 88.5%, while the ductility improved by 44.73% and the initial stiffness increased from 5.00 kN/mm to 7.01 kN/mm.

6. Compared with CFRP and RC jacketing, the UHPC strengthening system demonstrated superior confinement efficiency, improved crack control, greater stiffness retention, and significantly higher energy dissipation capacity throughout the cyclic loading history.

7. Damage distribution obtained from the numerical simulations indicated that all strengthening techniques reduced the concentration of damage at the beam–column joints and column bases. Nevertheless, UHPC produced the most uniform stress distribution and the lowest damage intensity, although localized crushing remained visible in limited regions subjected to severe stress concentrations.

8. The comparative numerical investigation confirmed that the effectiveness of each strengthening technique depends on the desired seismic performance objective. CFRP provides an efficient solution for improving ductility with minimal increase in structural dimensions, RC jacketing primarily enhances strength and stiffness, whereas UHPC offers the most balanced improvement by simultaneously increasing strength, stiffness, ductility, and energy dissipation capacity.

9. The unified numerical framework adopted in this study enabled a direct comparison between different strengthening techniques under identical modeling assumptions and loading conditions. This approach minimizes uncertainties associated with comparing results from different experimental programs and represents one of the principal contributions of the present research.

10. Overall, UHPC strengthening proved to be the most effective seismic retrofitting technique among the investigated methods, providing the optimum combination of structural strength, stiffness, ductility, damage control, and cyclic stability for reinforced concrete frames subjected to earthquake loading.

5.2 Future Work

Based on the findings of this research, the following recommendations are proposed for future studies:

1. Investigate the seismic response of strengthened reinforced concrete frames under recorded earthquake ground motions using nonlinear dynamic time-history analysis.

2. Evaluate the influence of different UHPC thicknesses, CFRP layer configurations, anchorage systems, and RC jacketing dimensions on the seismic performance of reinforced concrete frames.

3. Extend the proposed finite element methodology to multi-story and irregular reinforced concrete buildings in order to investigate global structural behavior under severe seismic events.

4. Conduct full-scale experimental testing to further validate the developed numerical models and improve the calibration of nonlinear constitutive parameters.

5. Investigate the long-term durability of UHPC, CFRP, and RC jacketing systems considering environmental effects, corrosion, fatigue loading, and repeated earthquake events.

6. Perform life-cycle cost and sustainability assessments to compare the economic efficiency of different strengthening techniques for practical rehabilitation projects.

7. Develop hybrid strengthening systems combining UHPC with CFRP or other advanced materials to further enhance seismic performance and damage resistance.

8. Compare UHPC strengthening with modern seismic protection systems, such as supplemental dampers and base isolation devices, in terms of structural performance, energy dissipation, construction feasibility, and cost-effectiveness.

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