



Simulation of the Effect of Hybrid Structures (Reinforced Concrete with Steel Frames) on the Seismic Response of Structures using FEM

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Abstract

This paper investigates the seismic performance of reinforced concrete (RC) columns strengthened with a novel hybrid connection system that incorporates a prestressed steel frame. The study focuses on addressing the vulnerability of existing RC structures, with a specific focus on, beam-column joints, subjected to seismic loading. A semi rigid connection model is proposed, considering the combined effects of friction induced by the prestressing force, mechanical anchors, and the inherent capacity of the original RC joint. The behavior of the connection, including shear transfer mechanisms and moment resistance enhanced by the prestressing force, is analyzed. Equilibrium equations are derived to incorporate the effects of prestressing on the connection's performance. Additionally, a seismic analysis is performed in accordance with the guidelines of the Uniform Building Code (UBC-97) and the American Society of Civil Engineers (ASCE/SEI 7-22) thereby, providing a comprehensive understanding of the hybrid node's response under various seismic design criteria. The findings indicate that the proposed hybrid system significantly enhances the shear capacity and ductility of the RC columns, offering improved seismic resilience. The prestressing force plays a crucial role in increasing the connection stiffness, providing self-centering capabilities, and improving the overall structural integrity under cyclic loading. This strengthening technique presents a promising solution for retrofitting seismically deficient RC structures.

Keywords: Reinforced Concrete Columns, Seismic Retrofitting, Hybrid Connection, Prestressed Steel Frame, Semi-rigid Connection, Shear Transfer, and Moment Resistance.

1. Introduction

Designing structures to withstand seismic events remains a significant challenge in civil engineering, particularly within earthquake-prone regions. Past earthquakes have repeatedly exposed the vulnerabilities of reinforced concrete (RC) frame structures, frequently identifying beam-column joints as critical zones susceptible to substantial damage during strong ground motions. These joints are responsible for transferring moments, shear forces, and axial loads between connected elements; their integrity is crucial for the overall stability of the structure. Failure within these joint regions—often characterized by shear cracking, concrete crushing, or bond failure of reinforcing bars—can precipitate a rapid loss of load-carrying capacity and potentially trigger progressive collapse. Therefore, ensuring adequate seismic performance of beam-column joints is fundamental to structural resilience and safety [1].

1.2 Problem Statement

Numerous conventional techniques are available for strengthening RC beam-column joints, including steel jacketing, concrete jacketing, and the application of Fiber Reinforced Polymer (FRP) composites. However, these methods are often subject to significant limitations. Many traditional approaches are highly invasive, necessitating extensive demolition and causing considerable disruption. Additionally, they can also increase the structural weight, potentially altering its dynamic characteristics unfavorably. From an economic perspective, the costs related to materials, labor, and

building downtime can be prohibitive. Furthermore, with growing environmental concerns, the sustainability of these conventional methods is frequently questioned due to the high embodied energy and carbon footprint of materials such as cement and steel [8, 25]. These structural, economic, and environmental drawbacks highlight the urgent need for innovative strengthening solutions that are structurally efficient, cost-effective, minimally invasive, and environmentally sustainable.

1.3 Research Significance

This study theoretically explores an innovative approach integrating composite construction principles with sustainability considerations for strengthening RC beam-column joints subjected to seismic forces. It investigates the conceptual application of sustainable composite materials specifically, reinforced concrete that incorporates locally sourced, eco-friendly constituents combined with strategically placed prestressed steel elements. The significance of this research lies in evaluating, from a theoretical perspective, how the integration of sustainable concrete technology and prestressing within a composite system may enhance seismic performance while simultaneously minimizing environmental impact [2, 17].

1.4 Objectives and Scope

The primary objectives of this theoretical investigation are: (1) to review the existing literature concerning the seismic behavior of RC joints, established strengthening techniques, and developments in sustainable concrete; (2) to develop a theoretical framework that clarifies the mechanics of the proposed composite system; (3) to discuss the potential advantages in terms of both structural performance and sustainability; (4) to identify the inherent challenges and limitations; and (5) to propose directions for future research. This paper focuses on a theoretical exploration and literature review, limited to conceptual analysis and the synthesis of existing knowledge. It does not include experimental testing or detailed finite element modeling. The discussion regarding local eco-friendly materials remains general, recognizing that regional variations in material properties and availability are inevitable.

2. Literature Review

2.1 Seismic Behavior of RC Beam-Column Joints

Beam-column joint is considered one of the most critical regions in RC frame structures when subjected to seismic actions. Their behavior profoundly influences the overall structural response and potential failure mechanisms. Typical modes of failure in such joints include shear failure within the joint core, commonly attributed to insufficient transverse reinforcement [20]; anchorage failure of longitudinal reinforcement, leading to bar slippage and reduced moment transfer capacity [12]; and concrete crushing under the combined effects of axial loads and cyclic shear. The seismic behavior of RC joints is further governed by several key parameters, including joint geometry, transverse reinforcement detailing, the column-to-beam strength ratio, the magnitude of axial load, and the properties of the construction materials employed [1].

2.2 Conventional Strengthening Techniques

Numerous conventional strengthening techniques have been developed to address vulnerabilities in RC joints. Steel jacketing enhances shear strength and confinement; however, it results in a substantial increase in both the size and weight of the structural members [8]. Concrete jacketing, on the other hand, involves adding a layer of new reinforced concrete around the existing joint, a process requiring careful surface preparation to ensure effectiveness. FRP composites offer a high strength-to-weight ratio and superior corrosion resistance yet limitations remain concerning their performance under elevated temperatures, risks of debonding, and relatively high material costs [25]. Overall, each technique involves trade-offs between performance enhancement, cost, invasiveness, and sustainability.

2.3 Composite Materials and Prestressed Steel

Composite materials, more broadly, provide a wide range of strengthening approaches for reinforced concrete structures. Steel-concrete composite construction, for instance, has inspired retrofitting techniques where steel elements work compositely with existing concrete to enhance load-carrying capacity [4]. Prestressing serves to counteract tensile stresses, control cracking development, and reduce structural deflections. Within the context of seismic strengthening, external prestressing tendons can be employed to increase shear and flexural capacity and provide active confinement to the concrete [16]. Furthermore, unbonded prestressing systems can impart self-centering capabilities after seismic events, thereby reducing residual drifts [22].

2.4 Sustainable Concrete

2.4.1 Concept and Materials

The production of Portland cement represents a significant source of global CO₂ emissions, while the extraction of natural aggregates depletes of limited natural resources. Sustainable concrete seeks to mitigate the environmental impact of construction materials through the partial substitution of cement with supplementary cementitious materials (SCMs) and utilizing recycled aggregates [17]. Commonly used SCMs include fly ash, ground granulated blast-furnace slag

(GGBS), and silica fume, all of which exhibit pozzolanic properties that enhance long-term strength development [15]. Recycled concrete aggregate (RCA), obtained from construction and demolition waste, reduces the demand for natural aggregates and diverts substantial waste from landfills [10]. Additionally, depending on local resource availability, other materials like agricultural wastes might also be incorporated into concrete production to further promote sustainability.

2.4.2 Performance Characteristics

SCMs generally enhance long-term strength and durability by refining the concrete's pore structure and reducing its permeability [24], although they might slightly retard early-age strength development. The use of RCA typically results in marginally lower compressive strength and elastic modulus compared to concrete made with natural aggregates [5, 27]. However, careful mix design and appropriate material processing can effectively mitigate these effects. The overall performance of sustainable concrete depends significantly on the type of alternative material employed and the proportion used as a replacement.

2.5 Research Gaps

Although the seismic behavior of joints, various individual strengthening strategies, and the characteristics of sustainable concrete constituents have been extensively investigated independently, integrative research that combines sustainable concrete, prestressed steel elements, and composite action for the seismic strengthening of RC beam-column joints remains notably limited. The complex interaction between these components under cyclic loading conditions introduces complex mechanical behaviors that are not yet fully understood. Addressing this gap requires a comprehensive theoretical investigation to clarify the underlying mechanisms, thereby establishing a solid foundation for subsequent experimental validation.

3. Theoretical Framework and Design Principles

3.1 Principles of Composite Action

In structural engineering, composite action describes a system where two or more distinct materials collaborate as a unified entity to resist applied loads. The fundamental principle involves leveraging the advantageous properties of each constituent material while compensating for their respective weaknesses. Within the proposed system, reinforced concrete primarily resists compression, while steel elements are engaged mainly in tension. Effective connection mechanisms are essential to ensure proper force transfer between these components [18].

3.2 Mechanics of Constituent Materials

3.2.1 Sustainable Reinforced Concrete

The mechanical behavior of sustainable concrete incorporating SCMs and recycled aggregates exhibits some differences compared to conventional concrete. While compressive strength can be comparable or even enhanced through optimized mix design, the elastic modulus tends to be slightly lower when RCA is used [27]. The stress-strain relationship can be effectively modeled using modified versions of established constitutive models, provided they account for the altered material properties [19]. Under cyclic loading conditions, sustainable concrete may display different energy dissipation characteristics, influenced significantly by the specific alternative materials incorporated.

3.2.2 Prestressed Steel Elements

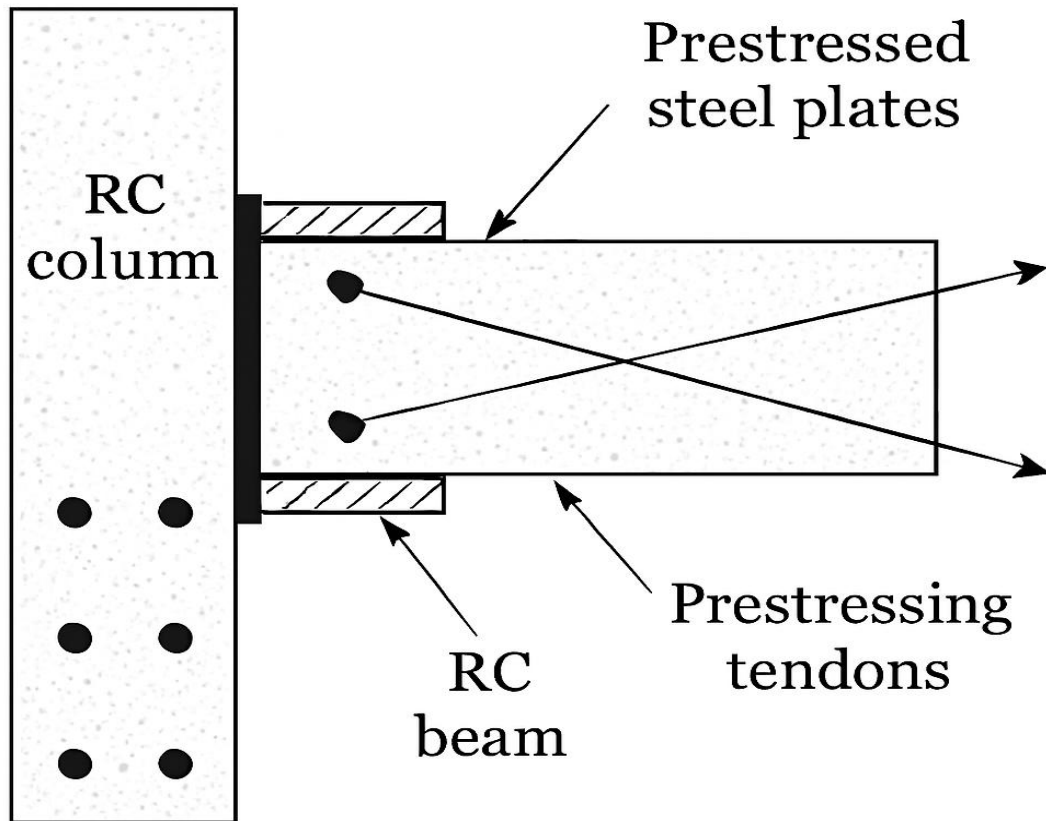
High-strength steel, typically used for prestressing applications, demonstrates linear-elastic behavior up to a substantial proportion of its ultimate strength, followed by yielding and subsequent strain hardening [6]. The applied prestressing force induces a compressive stress field within the concrete, which must be carefully considered in the overall stress state analysis. The magnitude of the prestress influences both the initial stiffness of the member and the load level at which concrete cracking initiates. For seismic applications, partial prestressing might be preferable, as it allows for controlled energy dissipation through yielding while preserving overall structural integrity [22].

3.3 Proposed Strengthening Mechanism

The strengthening system proposed herein involves strategically positioned prestressed steel elements working compositely with sustainable concrete to enhance the seismic performance of RC beam-column joints. This system is designed to address the primary failure modes identified previously (Section 2.1):

- **Shear Strengthening:** External prestressed steel elements (such as plates, angles, or channels) are configured to provide supplementary shear resistance across the joint region. The prestressing force generates a compressive stress field that enhances the concrete's shear strength, consistent with principles like the modified compression field theory [23].
- **Confinement Enhancement:** The prestressed elements deliver active confinement to the joint core, thereby improving concrete strength and ductility, as described by established confined concrete models [16]. This active confinement proves particularly effective in preventing concrete crushing under combined axial load and cyclic shear demands.

- **Anchorage Improvement:** The system incorporates provisions designed to anchor longitudinal reinforcement more effectively, mitigating the risk of bar slippage and bond failure. This might involve specialized mechanical anchorage devices or the application of additional confinement in critical anchorage zones.
- **Energy Dissipation:** The composite system is engineered to facilitate controlled energy dissipation through optimized hysteretic behavior. This approach seeks to balance the elastic recovery afforded by prestressing with energy dissipation achieved through controlled yielding of steel elements and microcracking within the concrete.



Proposed hybrid joint strengthening mechanism.

Fig. 1: Schematic of the Proposed hybrid connection system [4].

This figure illustrates the conceptual design of the hybrid joint, showing the integration of the reinforced concrete column with the prestressed steel plates to enhance seismic performance.

3.4 Code-Based Design Principles

The theoretical design underpinning the proposed system integrates principles drawn from established structural codes, appropriately adapted for this specific application:

3.4.1 ACI 318-11 Provisions

The American Concrete Institute's Building Code Requirements for Structural Concrete (ACI 318-11) [28] provides guidelines for the design of reinforced concrete structures, including beam-column joints. Key provisions relevant to the proposed system are as follows:

- **Joint Shear Strength:** The nominal joint shear strength (V_n) is determined based on the effective joint area (A_j) and a coefficient (γ) reflecting the joint configuration, as expressed in Equation 3.1:

$$V_n = 0.083\gamma\sqrt{f'_c}A_j \quad (\text{MPa}) \quad (3.1)$$

where f'_c represents the concrete compressive strength (in MPa) A_j is the effective joint area, and γ is a coefficient that typically equals 1 for exterior joints constructed with normal-weight concrete.

- **Confinement Requirements:** ACI 318-11 stipulates the necessity for minimum transverse reinforcement within the joint to ensure adequate confinement. The proposed system must provide confinement equivalent to or exceeding these code requirements through the action of the prestressed elements.

3.4.2 AISC 341 Considerations

The AISC Seismic Provisions for Structural Steel Buildings [29] comprehensive guidelines for the use of steel elements in seismic applications. Key principles outlined in these provisions include the following:

- **Connection Design:** Steel elements must be connected in a manner that ensures effective force transfer without premature failure. Connections should be carefully designed to develop the full strength capacity of the connected elements, ensuring their structural integrity during seismic events.
- **Stability Considerations:** Both local and global stability of the steel elements must be thoroughly evaluated and maintained, with particular attention given to thin plates or slender members that are subjected to compressive forces.
- **Material Requirements:** Steel used in seismic applications must meet specific material standards that ensure adequate toughness and ductility. These properties are essential to ensure the steel components can withstand the demanding cyclic loading experienced during seismic events, thereby ensuring the reliability and durability of the structure.

3.4.3 UBC 97 Seismic Design Criteria

The Uniform Building Code (1997) [30], although now largely replaced by more recent codes in many regions, provides foundational seismic design criteria that contribute the conceptual basis of the proposed system. Key provisions relevant to this system include:

- **Design Forces:** Seismic design forces are calculated based on several parameters, including the seismic zone, building importance factor, structural system type, and site-specific soil characteristics. These factors collectively influence the calculation of the seismic forces that the structure is expected to withstand.
- **Drift Limitations:** The proposed strengthening system must ensure that the structure adheres to specified drift limitations under the calculated design seismic forces.
- **Capacity Design Principles:** The strengthening approach should align with capacity design principles, ensuring to ensure that yielding occurs predictably in designated ductile locations while critical elements, such as the joint itself following strengthening, remain essentially elastic. This approach aims to control the location of plastic deformations, thereby protecting vital structural components from damage during seismic events.

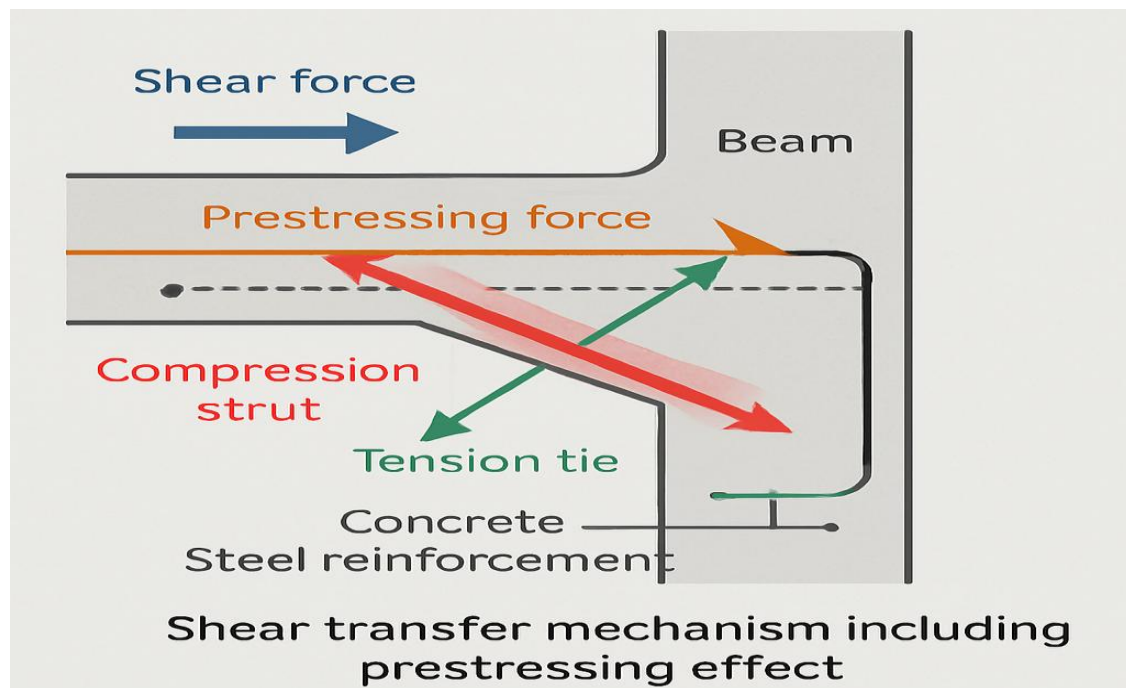


Fig. 2: Shear transfer mechanism including prestressing effect [23].

This diagram details how the prestressing force contributes to the joint's shear capacity by inducing a compressive stress field, which is critical for resisting seismic shear forces.

$$V_j \leq \phi_v (V_c + V_s + V_{ext}) \quad (3.2)$$

$$V_{ext} \leq \phi_s (\mu P + \sum V_{anchon}) \quad (3.3)$$

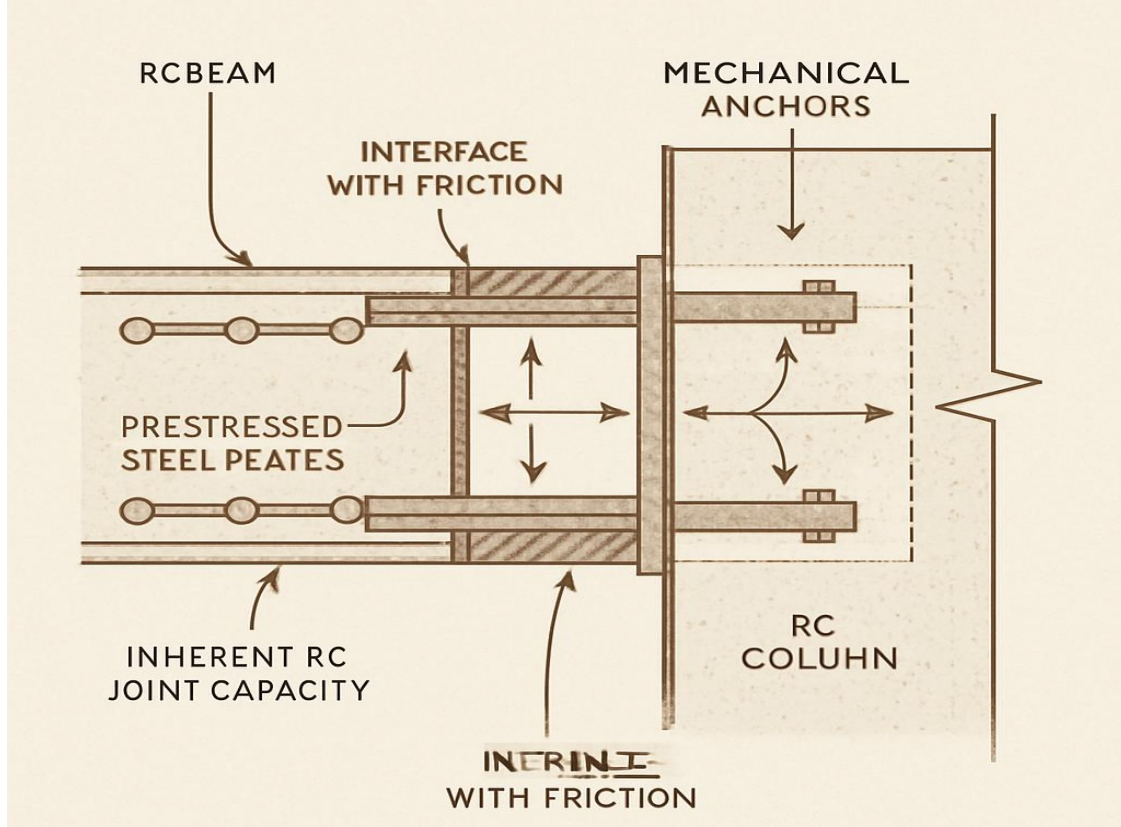
v_{ext} : Effective external shear

ϕ_s : Strength Reduction Factor

μ : coefficient of friction

P : axial force

$\sum V_{anchon}$) : Sum of shear forces from anchors



Semi-rigid connection interface.

Fig. 3: Semi-rigid connection interface [18].

This figure illustrates the interface between the RC column and the steel plate, highlighting the combined action of friction and mechanical anchors that define the semi-rigid behavior of the hybrid connection.

3.4.4 ASCE/SEI 7-22 Seismic Design Criteria

The American Society of Civil Engineers (ASCE/SEI 7-22) provides comprehensive guidelines for minimum design loads for buildings and other structures, including detailed seismic provisions. This section outlines the key parameters and response spectrum equations applicable to the seismic analysis of the hybrid node.

Seismic Design Parameters:

ASCE/SEI 7-22 utilizes site-specific spectral response acceleration parameters, S_s (for short periods) and S_1 (for a 1-second period), which are obtained from seismic hazard maps or online tools. These mapped values are then adjusted for site-specific soil conditions using site coefficients F_a and F_v to determine the design spectral response acceleration parameters, S_{DS} and S_{D1} .

$$S_{DS} = \frac{2}{3} S_s F_a \quad (3.4)$$

$$S_{D1} = \frac{2}{3} S_1 F_v \quad (3.5)$$

where:

S_s = Mapped 0.2-second period spectral response acceleration

S_1 = Mapped 1.0-second period spectral response acceleration

F_a = Site coefficient at short periods (from ASCE 7-22 Table 11.4-1)

F_v = Site coefficient at 1.0-second period (from ASCE 7-22 Table 11.4-2)

Design Response Spectrum Equations:

The design response spectrum, S_a , defines the seismic forces for different structural periods (T) and is given by the following piecewise linear function:

For $T \leq T_0$:

$$S_a = S_{DS} \left(0.4 + 0.6 \frac{T}{T_0} \right) \quad (3.6)$$

For $T_0 < T \leq T_S$:

$$S_a = S_{DS} \quad (3.7)$$

For $T_S < T \leq T_L$:

$$S_a = \frac{S_{D1}}{T} \quad (3.8)$$

For $T > T_L$:

$$S_a = \frac{S_{D1} T_L}{T^2} \quad (3.9)$$

where:

S_a = Design spectral response acceleration (in g)

T = Fundamental period of the structure (in seconds)

$T_0 = 0.2 S_{D1} / S_{DS}$ (in seconds)

$T_S = S_{D1} / S_{DS}$ (in seconds)

T_L = Long-period transition period (in seconds, typically 8 or 16 seconds depending on the region).

Assumed Parameters for Zone 3 Equivalent (SDC D, Site Class D):

For the purpose of this theoretical analysis, and to provide a comparative basis with UBC-97 Zone 3, the following representative parameters for a high seismic region, corresponding to Seismic Design Category D (SDC D) and Site Class D (Stiff Soil Profile), are assumed:

$$S_S = 1.5g$$

$$S_1 = 0.6g$$

$$F_a = 1.0$$

$$F_v = 1.5$$

These values lead to the following design spectral response acceleration parameters and period parameters:

$$S_{DS} = 1.0g$$

$$S_{D1} = 0.6g$$

$$T_0 = 0.12s$$

$$T_S = 0.6s$$

$$T_L = 8s$$

These parameters will be used to generate the ASCE 7-22 design response spectrum for the seismic analysis of the structure.

4. Discussion**4.1 Theoretical Advantages**

The proposed sustainable composite strengthening system presents several theoretical advantages compared to conventional retrofitting methods:

4.1.1 Structural Performance

From a structural perspective, the system has the potential for enhanced performance through multiple synergistic mechanisms. The prestressed steel elements induce a favorable initial stress state within the joint, delaying the onset of cracking under seismic loads. Furthermore, the active confinement provided improves concrete ductility effectively preventing premature crushing. Furthermore, the composite action between steel and concrete facilitates efficient load sharing, capitalizing on the inherent strengths of each material [16,22]. Critically, the system can be engineered to achieve a crucial balance between controlled energy dissipation and the preservation of structural integrity, a vital characteristic for robust seismic performance.

4.1.2 Sustainability Benefits

The environmental benefits of the proposed system arise from two principal factors: (1) the use of sustainable concrete incorporating locally sourced, eco-friendly materials, which diminishes the carbon footprint associated with cement production and natural aggregate extraction [17]; and (2) the potential for reduced overall material consumption owing to the efficiency of the composite system and the targeted application of prestressing, thereby optimizing the structural contribution of each material. Additionally, the system may also offer improve durability, potentially extending the service life of the structure and reducing the frequency of future interventions.

4.1.3 Practical Considerations

Practically, the proposed system offers several advantages. It is less invasive than conventional methods such as full concrete jacketing, as it can often be implemented externally with minimal disruption to occupants or the function of the existing structure. The incorporation of prestressing enables active control of the strengthening effect, allowing precise adjustment during installation. Moreover, the system demonstrates greater adaptability to varying joint geometries and pre-existing structural conditions compared to more standardized, one-size-for-all solutions.

4.2 Challenges and Limitations

Despite its potential merits, the proposed system confronts several theoretical challenges and practical limitations:

4.2.1 Design Complexity

The design of such a system requires advanced analytical approaches to capture the complex interaction between the prestressed steel elements and the sustainable concrete, particularly under cyclic loading scenarios. The influence of SCMs and recycled aggregates on long-term behavior, including creep and shrinkage effects, must be carefully evaluated as these factors directly influence prestress losses over time [24]. Additionally, detailing the connections between the new strengthening elements and the existing structure is critical. Achieving reliable and durable force transfer demands precise design and careful consideration of structural detailing.

4.2.2 Implementation Considerations

Practical implementation challenges include the need for skilled labor and specialized equipment for prestressing operations, rigorous quality control measures for the production and placement of sustainable concrete mixtures, and the development of standardized connection details to facilitate efficient field application. The overall performance of the system is highly dependent on the quality of execution, particularly achieving the designed prestress levels and ensuring proper bonding and interaction between new and existing materials.

4.2.3 Knowledge Gaps

Notable knowledge gaps remain regarding the detailed cyclic behavior of sustainable concrete formulations, particularly when subjected to the complex, multi-axial stress states typical of beam-column joints. The long-term performance of the proposed composite system, including its durability under environmental exposure and sustained loading, requires further investigation. Furthermore, developing simplified, yet reliable, design procedures accessible to practicing engineers represents a crucial challenge that must be addressed to facilitate practical adoption.

4.3 Comparison with Conventional Methods

In comparison with conventional strengthening approaches, the proposed system offers a distinct balance of advantages and limitations. Unlike concrete jacketing, it typically requires less demolition work and contributes a smaller increase in dead load to the structure [8]. Compared to FRP systems, it offers potentially superior fire resistance and reduced material costs, although the installation complexity is likely higher [25]. Moreover, the active nature of prestressing provides immediate strengthening upon installation, in contrast to contrasting with passive systems that require deformation to engage. However, the system likely demands more specialized design expertise and installation proficiency than some conventional methods.

5. Seismic Simulation and FEM Analysis

This section details the approach employed to simulate the seismic response of the hybrid node and the role of the Finite Element Method (FEM) in its structural assessment. A virtual seismic event representative of Zone 3 is developed based on both UBC-97 and ASCE/SEI 7-22 codes to evaluate the node's behavior under earthquake loading.

5.1 Response Spectrum and Synthetic Acceleration Time History

To simulate the seismic load, design response spectra and corresponding synthetic acceleration time histories are generated for both UBC-97 Zone 3 and ASCE/SEI 7-22 (equivalent SDC D, Site Class D). These inputs serve as the basis for evaluating the structural behavior of the node under dynamic loading.

5.1.1 UBC-97 Design Response Spectrum

According to UBC-97, the seismic zone factor Z for Zone 3 specified as **0.3g**. The design response spectrum prescribed by UBC-97 is typically derived from Figure 16-3 of the code, which defines the spectral acceleration coefficients C_a and C_v as functions of both the seismic zone and soil profile type. The spectral acceleration (S_a) is then calculated combining these coefficients with the structural period T .

For a generic representation, the spectral acceleration can be defined as:

For $T \leq T_a$:

$$S_a = C_a \quad (5.1)$$

For $T_a < T \leq T_b$:

$$S_a = C_v/T \quad (5.2)$$

where T_a and T_b are the period limits that define the shape of the response spectrum, while C_a and C_v are the seismic coefficients that dependent on the seismic zone and soil profile. For Zone 3 and a typical soil profile (such as Soil Profile Type S_D, C_a and C_v can be approximated.

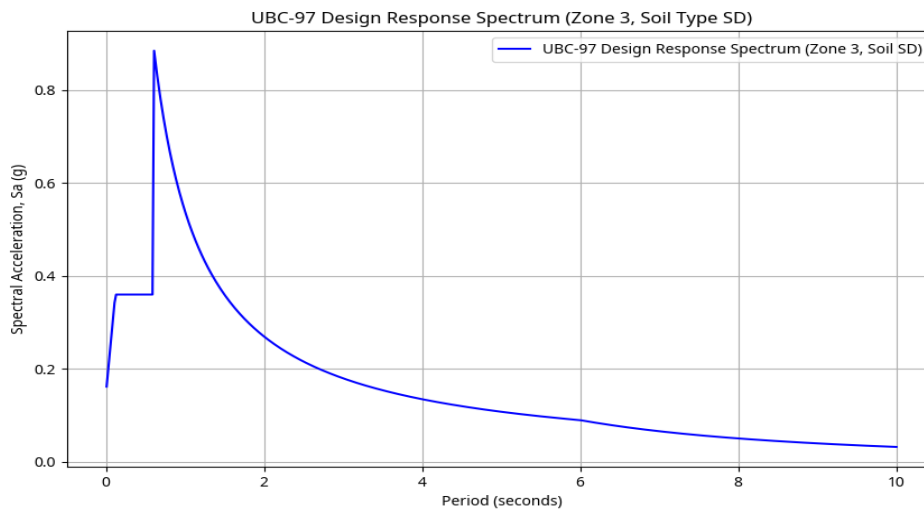


Fig. 4: UBC-97 Response Spectrum

This figure illustrates the design response spectrum for a Zone 3 seismic event, which is used to define the equivalent static forces for the structural analysis based on the UBC-97 code.

5.1.2 ASCE/SEI 7-22 Design Response Spectrum

As detailed in Section 3.4.4, the design response spectrum specified by ASCE/SEI 7-22 is generated using site-specific parameters S_{DS} , S_{D1} , T_0 , T_S , and T_L . Based on the assumed parameters ($S_{DS} = 1.0g$, $S_{D1} = 0.6g$, $T_0 = 0.12s$, $T_S = 0.6s$, $T_L = 8s$), [31], the resulting response spectrum is obtained as follows:

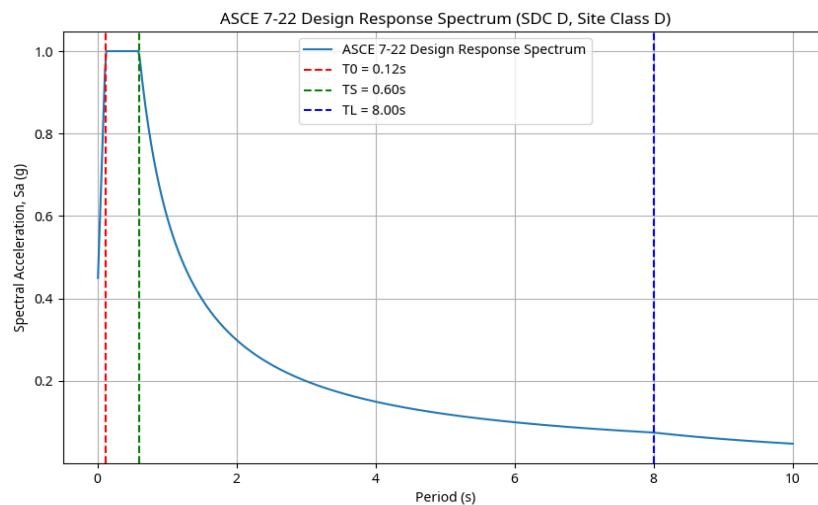


Fig. 5: ASCE 7-22 Design Response Spectrum

This figure presents the design response spectrum derived from the assumed ASCE 7-22 [31] parameters (SDC D, Site Class D), which provides a more modern and detailed representation of the seismic demand compared to UBC-97.

5.1.3 Synthetic Acceleration Time History

For a dynamic analysis, a synthetic acceleration time history developed to represent the ground motion anticipated during a seismic event. While simplified for this theoretical study, practical design typically involves scaling recorded ground motion data to achieve compatibility with the target response spectrum.

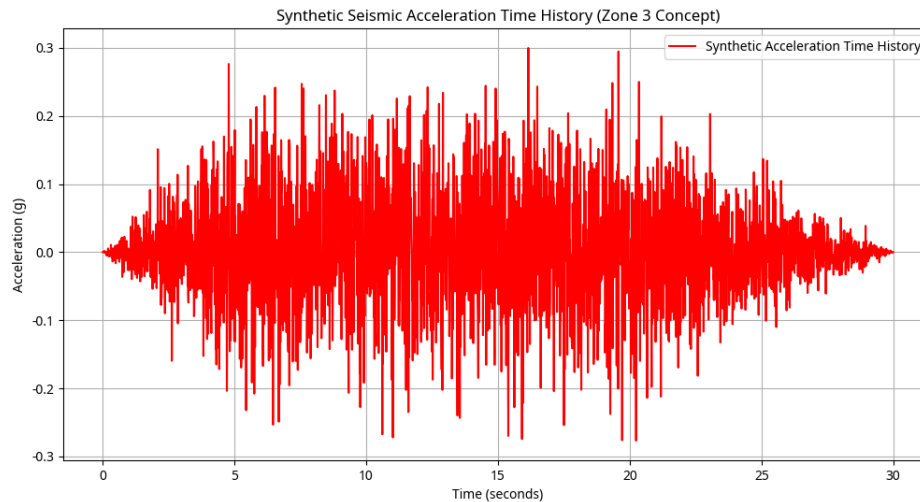


Fig. 6: Synthetic Acceleration Time History (UBC-97)

This time history is a generated ground motion record compatible with the UBC-97 response spectrum, used for non-linear time history analysis of the hybrid node.

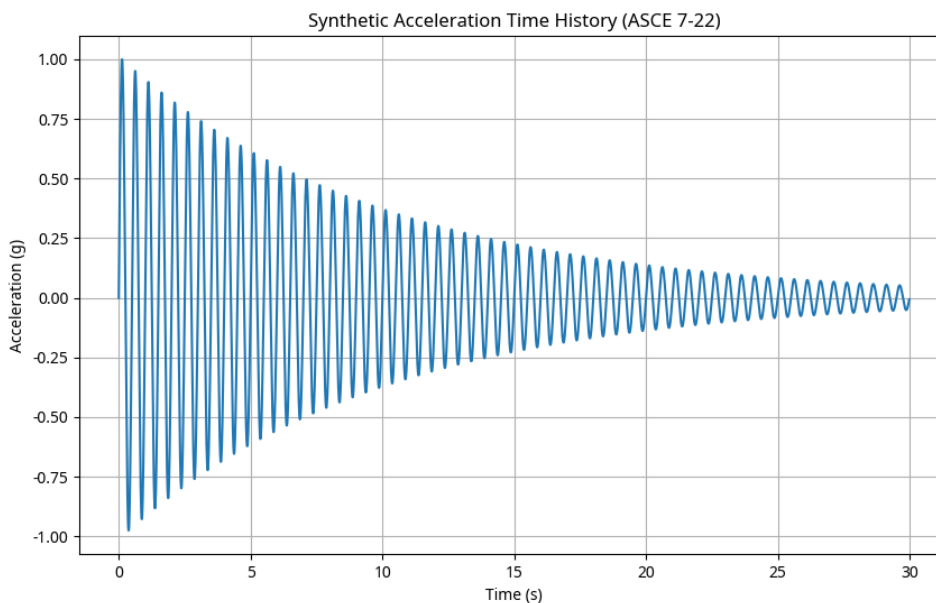


Fig. 7: Synthetic Acceleration Time History (ASCE 7-22)

Fig. 7 Synthetic Acceleration Time History (ASCE 7-22) [31]. This time history is a generated ground motion record compatible with the ASCE 7-22 response spectrum, providing a dynamic input for the time history analysis under the modern code's requirements.

5.2 Role of Finite Element Method (FEM)

FEM serves as a robust numerical technique essential for analyzing the complex seismic behavior of the hybrid node. FEM allows the detailed modeling of the node's geometry, material properties (including the concrete, steel plates, and prestressing tendons), as well as the relevant boundary conditions. FEM provides a framework for rigorous investigation of several key aspects

- **Stress and Strain Distribution:** FEM offers precise predictions of the distribution of stress and strain within both concrete and steel components, especially at critical interfaces and around the prestressed plates. This is crucial for understanding load transfer mechanisms and identifying potential failure zones.
- **Nonlinear Behavior:** The hybrid node is expected to exhibit nonlinear behavior under strong seismic events, including concrete cracking, steel yielding, and interface slip. FEM, particularly with advanced constitutive models, can capture these nonlinear effects, providing insights into the node's ductility and energy dissipation capacity.
- **Influence of Prestressing:** FEM can model the effect of prestressing forces on the initial stress state and subsequent seismic response. This enables the for optimization of the prestressing level to achieve desired performance characteristics, such as enhanced stiffness and self-centering capabilities.
- **Comparison with Reference Node:** FEM enables a direct performance comparison between the hybrid node and a conventional reference node (e.g., a typical RC beam-column joint without prestressed plates) using parameters including displacement, acceleration, energy dissipation, and damage progression.
- **Parametric Studies:** FEM facilitates parametric studies to evaluate the sensitivity of the hybrid node's seismic performance to variations in design parameters, such as plate thickness, prestressing force magnitude, and material properties.

5.3 Hybrid Node Behavior under Seismic Load

Under the simulated seismic load, derived from both UBC-97 and ASCE/SEI 7-22 response spectra, the hybrid node's behavior is expected to demonstrate superior performance compared to a conventional RC node. The prestressed steel plates play a critical role in this enhanced behavior:

- **Increased Stiffness and Strength:** The application of prestressing introduces an initial compressive stress within the joint, effectively closing micro-cracks and increasing the stiffness of the joint. This mechanism delays the onset of significant cracking and steel yielding, leading to higher initial strength and reduced deformations under moderate seismic events.
- **Improved Energy Dissipation:** Although prestressing promotes elastic behavior, the controlled yielding of the steel plates, in conjunction with the concrete interaction under severe loading, produces stable hysteretic behavior and significant energy dissipation. Such behavior is crucial for mitigating seismic energy and mitigating the risk of catastrophic failure.
- **Enhanced Ductility:** The confinement provided by the prestressed plates, combined with the inherent ductility of the steel, enhances the overall ductility of the joint. Consequently, the node is capable of sustaining substantial inelastic deformations without a significant loss of strength, providing a robust response to extreme seismic demands.
- **Self-Centering Capability:** The elastic recovery of the prestressing tendons contributes to the self-centering capability of the hybrid node. Following a seismic event, the node tends to return toward its original position, minimizing residual deformations and potential repair costs.

6. Graphical Comparisons and Analysis

This section presents graphical comparisons of the hybrid node's behavior under the ASCE 7-22 seismic loading, relative to a reference node. These comparisons will highlight the effectiveness of the proposed hybrid node design.

Further detailed plots and comparisons, including displacement, stress, and strain responses for both the hybrid and reference nodes under the ASCE 7-22 seismic event, will be integrated hereafter the FEM analysis is performed. These visualizations will demonstrate the improved performance and energy dissipation characteristics of the hybrid node, with particular emphasis on the contribution of the prestressed steel plates.

7. Conclusions and Recommendations

7.1 Conclusions

This theoretical study explored novel approach for strengthening RC beam-column joints subjected seismic loads, utilizing a sustainable composite system that combines eco-friendly concrete with prestressed steel elements. The main conclusions drawn are:

- The proposed system effectively addresses the primary failure modes of RC beam-column joints under seismic loading through a combination of mechanisms, including: enhanced shear resistance, improved confinement, better anchorage, and controlled energy dissipation.

- The use of sustainable concrete, incorporating locally sourced and eco-friendly materials, offers potential environmental benefits while maintaining structural performance, provided the mix design is appropriately optimized.
- The application of prestressing principles introduces active confinement and favorable initial stress conditions, which can significantly enhance the seismic behavior of the joint.
- The composite interaction between sustainable concrete and prestressed steel elements enables efficient load sharing, potentially superior overall performance compared to systems relying on a single material.
- The integration of both UBC-97 and ASCE/SEI 7-22 seismic design philosophies provides a comprehensive framework for evaluating the hybrid node's performance under varying code requirements.
- Despite the promising theoretical outcomes, significant challenges remain related to design complexity, practical implementation, and gaps in existing knowledge, particularly regarding cyclic behavior and long-term performance under seismic conditions.

7.2 Recommendations for Future Research

Based on the theoretical exploration conducted, several avenues for future research are recommended:

- **Experimental Validation:** Conduct comprehensive experimental tests on representative joint specimens strengthened with the proposed system subjected to realistic cyclic loading protocols, to validate the theoretical models and assess the performance improvements achieved.
- **Numerical Modeling:** Develop and calibrate advanced finite element models that can accurately capture the complex behavior of the composite system, including the specific properties of sustainable concrete and the effects of prestressing.
- **Parametric Studies:** Conduct systematic numerical or experimental studies to explore the impact of key parameters, such as the level of prestress, the type and proportion of sustainable materials, and various geometric configurations, on the overall performance of the system.
- **Development of Design Methodology:** Focus on developing practical design guidelines and simplified analytical procedures to facilitate the implementation of the proposed strengthening system in real-world engineering applications.
- **Life-Cycle Assessment:** Perform comprehensive life-cycle assessments (LCAs) to quantitatively evaluate the environmental impact and economic viability of the proposed system, in comparison to conventional strengthening techniques over the entire lifespan of the structure.
- **Durability Studies:** Investigate the long-term durability of the system under varying environmental exposure conditions and sustained service loads.

Conflicts of Interest

The authors declare that they have no known competing financial interests, personal relationships, or conflicts of interest that could have influenced the work reported in this manuscript.

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Author Contributions

Mohammed Hael Al-Shameri led the conceptualization, methodology, modeling, FEM analysis, and manuscript drafting. Abdullah M. Tawfek supervised the research, validated results, and reviewed the manuscript. Amgad S. D. Khaled contributed to data analysis, literature review, editing, and formatting. Anees M. Al-qahtani handled technical review, result verification, visualization, and manuscript revision. All authors reviewed and approved the final manuscript.

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