International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 08 | Aug 2026 www.irjet.net p-ISSN: 2395-0072

PERFORMANCE EVALUATION OF HIGH-STRENGTH CONCRETE AND ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC) IN HIGH-RISE RC BUILDINGS UNDER SEISMIC LOADING: A REVIEW STUDY

Md Arif Raza[1], Mr. Ushendra Kumar[2]

[1]*Master of Technology, Civil Engineering, Lucknow Institute of Technology, Lucknow, India*
[2]*Head of Department, Department of Civil Engineering, Lucknow Institute of Technology, Lucknow, India*

Abstract - *The increasing demand for high-rise reinforced concrete (RC) buildings in seismic regions has encouraged the adoption of advanced cementitious materials with enhanced strength, durability, and structural efficiency. High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) offer significant advantages over conventional concrete, including higher compressive strength, improved durability, reduced member dimensions, and enhanced crack resistance. However, their seismic performance, particularly with respect to ductility, energy dissipation, cyclic degradation, and failure mechanisms, requires critical evaluation. This review study presents a comprehensive assessment of the performance of HSC and UHPC in high-rise RC buildings subjected to seismic loading. The review examines material characteristics, mechanical and fracture properties, cyclic behavior, and the response of critical structural components, including beams, columns, beam-column joints, shear walls, and coupling beams. Furthermore, experimental, analytical, and numerical approaches used for seismic performance evaluation are critically discussed. Key performance indicators, including strength, stiffness degradation, ductility, interstory drift, energy dissipation, damage progression, and residual deformation, are evaluated. The study also examines the applicability of existing seismic design provisions and identifies critical research gaps related to full-scale validation, nonlinear dynamic analysis, performance-based seismic design, and post-earthquake resilience. Finally, future research directions are proposed to support the safe, efficient, and sustainable application of HSC and UHPC in high-rise seismic-resistant RC structures.*

Key Words: High-Strength Concrete (HSC); Ultra-High-Performance Concrete (UHPC); High-Rise Buildings; Seismic Loading; Reinforced Concrete; Cyclic Behavior; Seismic Performance

1. INTRODUCTION

1.1 Background

1.1.1 Growth of High-Rise Buildings

The rapid growth of urbanization, population, and land scarcity has increased the demand for high-rise and supertall buildings. As building height increases, structural systems are subjected to greater gravity loads, wind forces, and seismic demands. These conditions require materials with high strength, stiffness, durability, and structural efficiency. Consequently, concrete technology has evolved from conventional concrete toward High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC), which can provide higher load-carrying capacity, improved durability, reduced member dimensions, and better crack resistance.

1.1.2 Increasing Structural Demands

High-rise buildings require structural members capable of resisting substantial axial forces, bending moments, shear forces, and lateral loads. The use of HSC and UHPC can reduce the size of heavily loaded columns and shear walls, thereby increasing usable floor space and potentially reducing structural weight. However, their high strength and stiffness must be carefully evaluated under seismic loading because strength alone does not ensure adequate ductility and energy dissipation.

1.2 Seismic Challenges in High-Rise RC Buildings

1.2.1 Dynamic Response and Inertial Effects

High-rise RC buildings exhibit complex dynamic behavior due to their large mass, flexibility, and multiple vibration modes. Higher-mode effects and long-period ground motions can significantly influence seismic response. The use of HSC and UHPC may alter the mass, stiffness, and natural period of a building, thereby affecting its dynamic behavior during earthquakes.

1.2.2 Drift and P–Δ Effects

Interstory drift is a critical parameter in assessing seismic performance because excessive drift can cause structural and nonstructural damage. In high-rise buildings, P–Δ effects caused by the interaction of gravity loads and lateral displacement can further amplify structural demands. Therefore, adequate stiffness, deformation capacity, and stability are essential for seismic safety.

1.2.3 Failure Mechanisms

During strong earthquakes, high-rise RC structures may experience plastic hinge formation, flexural failure, shear failure, beam-column joint damage, and shear wall degradation. HSC may exhibit brittle compression failure if adequate confinement is not provided, while UHPC and fiber-reinforced UHPC can improve crack control and post-cracking behavior. However, proper seismic detailing and capacity design remain essential to ensure ductile structural behavior.

1.2.4 Foundation–Structure Interaction

The seismic response of high-rise buildings is also influenced by foundation and soil conditions. Large overturning moments and vertical loads are transferred to the foundation during earthquakes, while soil flexibility and foundation movement can modify the dynamic response of the structure. Therefore, soil-structure interaction should be considered when evaluating the seismic performance of high-rise buildings using advanced concrete materials.

1.3 Development of HSC and UHPC

1.3.1 Evolution of Concrete Technology

Concrete technology has progressed from conventional concrete to High-Performance Concrete (HPC), High-Strength Concrete (HSC), and Ultra-High-Performance Concrete (UHPC). Conventional concrete provides adequate strength for general structural applications, whereas HPC focuses on improving overall performance, including strength, durability, workability, and permeability. HSC provides significantly higher compressive strength, while UHPC offers exceptional strength, durability, and fracture resistance.

1.3.2 Mechanical and Durability Characteristics

The development of HSC and UHPC has resulted in improvements in compressive strength, tensile strength, fracture energy, and durability. UHPC possesses a highly refined and dense microstructure with very low permeability, while fiber-reinforced UHPC can provide improved tensile behavior and crack bridging. These properties make HSC and UHPC promising materials for high-rise and seismic-resistant construction.

2. REVIEW METHODOLOGY

The review methodology provides a systematic framework for identifying, selecting, analyzing, and synthesizing existing research related to the seismic performance of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) in high-rise reinforced concrete (RC) buildings. A well-defined methodology enhances the reliability, transparency, and academic rigor of the review by ensuring that relevant studies are systematically identified and evaluated. The present review considers research at different levels, ranging from material properties and structural components to complete building systems, with particular emphasis on seismic and cyclic behavior.

2.1 Literature Search Strategy

2.1.1 Database Selection and Search Process

A systematic literature search is conducted using major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, ASCE Library, Wiley Online Library, Taylor & Francis, and Google Scholar. These databases are selected to obtain a broad and multidisciplinary collection of peer-reviewed research papers related to concrete technology, structural engineering, earthquake engineering, and high-rise construction. Google Scholar is considered primarily as a supplementary source for identifying additional relevant publications that may not be indexed in the major academic databases.

The literature search covers a suitable publication period to capture both the historical development and recent advancements in HSC, UHPC, and seismic-resistant RC structures. Appropriate keywords and Boolean operators such as AND and OR are used to refine the search and identify studies directly relevant to the research topic. Representative search combinations include ("high-strength concrete" OR HSC) AND ("seismic" OR "cyclic loading") AND ("high-rise" OR "tall building"), ("ultra-high-performance concrete" OR UHPC OR UHPFRC) AND ("earthquake" OR seismic) AND ("reinforced concrete"), and UHPC AND ("beam-column joint" OR column OR shear wall) AND cyclic. Additional combinations may be used to identify studies concerning ductility, energy dissipation, interstory drift, hysteretic response, nonlinear analysis, and performance-based seismic design.

2.2 Inclusion Criteria

2.2.1 Selection of Relevant Studies

The studies included in the review are selected according to predefined criteria to ensure their relevance and academic quality. Priority is given to peer-reviewed journal articles and high-quality conference papers that investigate the mechanical, structural, or seismic behavior of HSC, UHPC, or UHPFRC. Studies involving monotonic, cyclic, dynamic, or earthquake loading are considered where they provide meaningful information regarding structural performance under seismic conditions.

The review also includes research focusing on RC structural members and systems, such as beams, columns, beam-column joints, shear walls, coupling beams, and high-rise structural systems. Studies are considered suitable when they provide sufficient information regarding experimental procedures, numerical methods, material properties, loading conditions, and major findings, allowing meaningful comparison and critical synthesis of the available research.

2.3 Exclusion Criteria

2.3.1 Screening and Removal of Irrelevant Studies

Studies that do not satisfy the defined research objectives are excluded from the review. Duplicate publications identified across different databases are removed to avoid repetition and bias in the literature synthesis. Nontechnical articles, general reports, and publications lacking sufficient scientific or methodological information are also excluded. Research that is unrelated to the structural or seismic performance of HSC and UHPC is omitted unless it provides directly relevant information for understanding material behavior. Similarly, studies focusing exclusively on nonstructural applications or purely material-based applications without meaningful relevance to structural engineering are generally excluded. This screening process ensures that the final literature database remains focused on the seismic performance and structural application of advanced concrete materials in RC buildings.

2.4 Literature Classification Framework

2.4.1 Classification of Selected Studies

The selected studies are systematically classified according to material type, structural scale, loading condition, structural component, research methodology, performance parameter, building height, and seismic design approach. This classification facilitates a structured comparison of the existing literature and helps identify research trends and knowledge gaps.

The material category distinguishes between HSC, UHPC, and UHPFRC, while the structural scale ranges from material-level investigations to component, subassembly, and complete building-level studies. The loading conditions are categorized as monotonic, cyclic, dynamic, or seismic. Structural components are classified into beams, columns, beam-column joints, shear walls, coupling beams, and core systems. Furthermore, the research methodology is categorized as experimental, numerical, or analytical.

The studies are also evaluated based on key performance parameters, including strength, stiffness, ductility, energy dissipation, interstory drift, damage development, and failure mechanisms. In terms of building configuration, studies are grouped according to low-rise, mid-rise, and high-rise structures. Finally, the seismic assessment approaches are categorized into force-based, displacement-based, and performance-based methods. This framework enables a systematic synthesis of research findings from the material scale to the complete structural system scale.

2.5 Bibliometric and Trend Analysis

2.5.1 Analysis of Research Trends

Where a sufficiently large body of literature is available, bibliometric analysis can be conducted to identify the development and emerging trends within the research field. Publication trends can be analyzed to determine the growth of research on HSC and UHPC under seismic loading over time. Citation analysis can further identify highly influential publications and major research contributions, while keyword co-occurrence analysis can reveal relationships among frequently studied research topics.

2.5.2 Research Clusters and Emerging Themes

Bibliometric analysis can also be used to identify major research clusters and emerging themes related to advanced concrete and seismic engineering. The geographical distribution of research can provide information regarding the countries and institutions contributing significantly to the field. Emerging topics such as UHPC structural applications, fiber-reinforced concrete, nonlinear seismic analysis, performance-based design, seismic resilience, and sustainable construction can also be identified through keyword and thematic analysis.

For this purpose, software tools such as VOSviewer, Bibliometrix/Biblioshiny, and CiteSpace may be employed. The results of such analysis can complement the systematic literature review by providing a quantitative overview of research development and helping to identify underexplored areas that require further investigation.

3. FUNDAMENTAL CHARACTERISTICS OF HSC AND UHPC

High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) represent significant developments in modern concrete technology. Their enhanced mechanical, microstructural, and durability characteristics make them attractive for high-rise reinforced concrete structures, particularly where high load-carrying capacity, reduced member dimensions, and long-term durability are required. However, their behavior differs from conventional concrete, particularly in terms of tensile response, fracture characteristics, shrinkage, and time-dependent behavior. A proper understanding of these fundamental characteristics is essential for evaluating their suitability for high-rise structures subjected to seismic loading.

3.1 Definition and Classification

3.1.1 Conventional Concrete, HSC, HPC, UHPC, and UHPFRC

Conventional concrete is primarily designed to provide adequate compressive strength, stiffness, durability, and workability for general structural applications. High-Strength Concrete (HSC) is developed to achieve substantially higher compressive strength than conventional concrete through the use of a low water-to-binder ratio, supplementary cementitious materials, and high-range water-reducing admixtures. High-Performance Concrete (HPC), in contrast, is a broader classification that emphasizes overall performance characteristics such as strength, durability, permeability, workability, and service life rather than compressive strength alone.

Ultra-High-Performance Concrete (UHPC) represents a further advancement in cement-based materials and is characterized by an extremely dense microstructure, very high compressive strength, low permeability, and improved tensile and fracture properties. When fibers are incorporated into UHPC to enhance tensile capacity, crack control, and post-cracking behavior, the material is generally referred to as Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC). Thus, high strength primarily refers to the ability of concrete to resist high compressive stresses, whereas high performance represents a broader concept involving multiple mechanical, durability, and serviceability properties. This distinction is particularly important when assessing seismic performance because high compressive strength alone does not necessarily ensure adequate ductility or energy dissipation capacity.

3.2 Constituent Materials

3.2.1 Cementitious and Mineral Constituents

The performance of HSC and UHPC is strongly influenced by the type and proportion of constituent materials. Portland cement provides the primary binding phase, while supplementary cementitious materials such as silica fume, fly ash, and ground granulated blast furnace slag contribute to improved particle packing, pozzolanic activity, strength development, and durability. Silica fume is particularly important in UHPC because its extremely fine particles fill microscopic voids and react with calcium hydroxide, producing a denser cementitious matrix. Fly ash and slag may also be incorporated to improve workability, durability, and sustainability, although their influence depends on their chemical composition and curing conditions.

3.2.2 Aggregates, Admixtures, and Fibers

UHPC commonly uses fine aggregates and quartz powder rather than conventional coarse aggregates to achieve a highly homogeneous and densely packed matrix. High-range water-reducing admixtures or superplasticizers are essential for maintaining workability despite the very low water-to-binder ratio. Fibers, particularly steel fibers, are frequently incorporated into UHPC to enhance tensile strength, fracture energy, crack control, and post-cracking resistance. The selection and proportioning of these constituents significantly influence the mechanical and fracture behavior of the final concrete and therefore have direct implications for structural and seismic performance.

3.3 Mix Design Principles

3.3.1 Low Water-to-Binder Ratio and Particle Packing

The mix design of HSC and UHPC is based on achieving high strength and a dense, homogeneous microstructure. A low water-to-binder ratio reduces capillary porosity and increases matrix strength, while superplasticizers provide the required workability. In UHPC, optimized particle packing is achieved by combining particles of different sizes to minimize voids and improve matrix density. This approach reduces permeability and enhances mechanical performance.

3.3.2 Pozzolanic Reaction and Microstructural Development

Supplementary cementitious materials, particularly silica fume, participate in pozzolanic reactions that refine the pore structure and improve the quality of the cementitious matrix. The resulting microstructural densification enhances compressive strength and durability. In fiber-reinforced UHPC, the incorporation of fibers must also be carefully controlled to achieve uniform distribution and effective crack bridging. Appropriate curing conditions, including heat or controlled curing where applicable, can further accelerate hydration and improve the development of mechanical properties. Therefore, mix proportioning, fiber incorporation, and curing conditions are critical factors governing the final performance of HSC and UHPC.

3.4 Microstructure

3.4.1 Matrix Densification and Interfacial Transition Zone

The superior performance of HSC and UHPC is closely associated with their refined microstructure. Compared with conventional concrete, UHPC generally possesses a much denser cementitious matrix with reduced capillary pores and a more homogeneous distribution of constituents. The interfacial transition zone between the cement paste and aggregate is also improved, reducing weak regions where cracking commonly initiates. This microstructural refinement contributes to higher strength and improved resistance to environmental deterioration.

3.4.2 Fiber-Matrix Interface and Crack Bridging

In UHPFRC, the fiber-matrix interface plays a major role in controlling crack development. When cracks form, fibers bridge the crack surfaces and transfer tensile stresses across them, thereby delaying crack localization and improving post-cracking resistance. This crack-bridging mechanism can result in multiple fine cracks rather than a single dominant fracture. Such behavior is potentially beneficial under cyclic seismic loading because it can improve crack control and energy absorption. However, the effectiveness of fiber reinforcement depends on fiber type, orientation, volume fraction, bond characteristics, and matrix quality.

3.5 Mechanical Properties

3.5.1 Strength and Elastic Properties

HSC and UHPC exhibit significantly higher compressive strength than conventional concrete, enabling structural members to resist greater axial and compressive forces with reduced dimensions. UHPC also generally exhibits improved splitting tensile, direct tensile, and flexural strengths, particularly when fibers are incorporated. These properties are important for structural components subjected to combined axial, bending, and shear demands in high-rise buildings.

The modulus of elasticity of HSC and UHPC is generally higher than that of conventional concrete, resulting in increased structural stiffness. However, the increased stiffness can influence the natural period and dynamic response of high-rise buildings under seismic excitation. Poisson's ratio is also relevant to the three-dimensional stress state of concrete, although its influence is generally less significant than strength and stiffness in structural seismic assessment.

3.5.2 Fracture Energy and Seismic Relevance

Fracture energy represents the energy required for crack propagation and is an important parameter for understanding the failure behavior of advanced concrete. UHPC and UHPFRC can exhibit higher fracture resistance due to their dense matrix and fiber-bridging mechanisms. This property can contribute to improved crack control and energy absorption under cyclic loading. However, the relationship between high material strength, fracture energy, ductility, and overall seismic performance remains an important area of research, particularly for high-rise RC structural systems.

4. SEISMIC BEHAVIOR OF HSC AND UHPC

The seismic performance of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) is governed by the interaction of strength, stiffness, ductility, deformation capacity, energy dissipation, and damage development under repeated and reversed loading. Although these materials provide superior mechanical properties compared with conventional concrete, their behavior under earthquake loading cannot be evaluated solely on the basis of compressive strength. High-rise reinforced concrete structures require controlled inelastic behavior, stable hysteretic response, and sufficient deformation capacity to withstand severe ground motions without sudden failure. Therefore, understanding the cyclic response of HSC and UHPC is essential for assessing their suitability for seismic-resistant structural applications.

4.1 Fundamental Seismic Requirements

4.1.1 Strength, Stiffness, and Ductility

Adequate strength and stiffness are essential requirements for the seismic performance of reinforced concrete structures. HSC and UHPC provide high compressive strength and increased elastic stiffness, allowing structural members to resist large axial and lateral forces with relatively smaller cross-sectional dimensions. This characteristic is particularly advantageous in high-rise buildings, where heavily loaded columns and shear walls may otherwise require large sections. However, high strength and stiffness must be accompanied by sufficient ductility and deformation capacity. A seismic-resistant structure should be capable of undergoing significant inelastic deformation while maintaining its load-carrying capacity and avoiding sudden brittle failure.

4.1.2 Energy Dissipation and Damage Tolerance

During a strong earthquake, structural members are expected to dissipate seismic energy through controlled inelastic behavior. The ability to dissipate energy through stable hysteretic cycles is therefore a fundamental requirement for seismic design. HSC may exhibit reduced deformation capacity if adequate confinement and reinforcement detailing are not provided, whereas UHPC, particularly UHPFRC, can improve crack control and post-cracking resistance through fiber bridging. Damage tolerance is also important because a structure should sustain localized damage without experiencing disproportionate loss of global strength. In addition, low residual drift is desirable because excessive permanent deformation can make a building difficult or uneconomical to repair after an earthquake.

4.2 Cyclic Stress-Strain Behavior

4.2.1 Response under Reversed Cyclic Loading

The stress-strain behavior of HSC and UHPC under cyclic loading differs considerably from their monotonic response. Under repeated compression, unloading, and reloading cycles, concrete experiences progressive microcracking and internal damage, resulting in changes in stiffness and strength. The response becomes more complex under seismic loading because structural members are subjected to repeated reversals between tension and compression. In HSC, the dense matrix can provide high compressive resistance but may also lead to relatively brittle behavior when the material reaches its ultimate compressive strain.

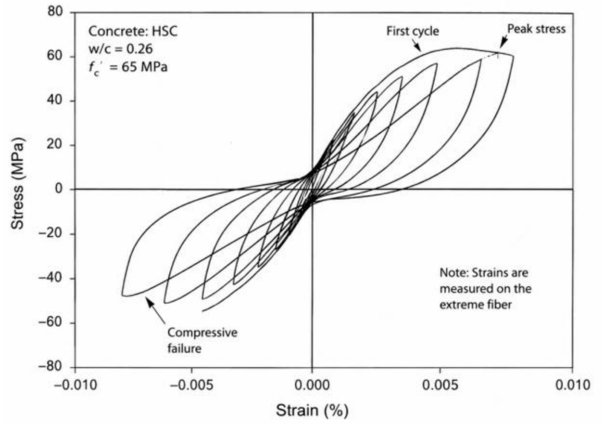

Figure 1: Cyclic Stress-Strain Behavior

4.2.2 Hysteretic Response and Degradation

Cyclic loading generally causes gradual stiffness and strength degradation as cracking and internal damage accumulate. Hysteretic response is commonly evaluated through load-displacement or stress-strain loops, which provide information regarding energy dissipation and cyclic stability. Pinching of hysteresis loops may occur because of crack opening and closure, bond deterioration, and reinforcement slip. UHPC and UHPFRC may exhibit improved hysteretic behavior because of their superior tensile resistance and fiber-bridging mechanisms, although the actual response depends on fiber content, reinforcement detailing, axial load, and structural configuration. Therefore, cyclic constitutive models used for seismic analysis should adequately represent stiffness degradation, strength deterioration, unloading-reloading behavior, and hysteretic pinching.

4.3 Ductility and Brittleness

4.3.1 Strength–Ductility Relationship

One of the major concerns associated with HSC is the possible conflict between increased compressive strength and deformation capacity. As concrete strength increases, the material may exhibit a steeper stress-strain response and reduced ultimate compressive strain, potentially resulting in brittle failure if the member is not adequately confined. Therefore, the use of HSC does not automatically guarantee improved seismic performance. The structural system must be designed to ensure that ductile flexural mechanisms develop before brittle shear or compression failure.

4.3.2 Role of Confinement and Transverse Reinforcement

Confinement provided by closely spaced transverse reinforcement can significantly improve the deformation capacity of HSC columns and other compression-dominated members. Transverse reinforcement restrains lateral expansion of concrete and delays crushing, thereby increasing the usable compressive strain and improving post-peak behavior. The effectiveness of confinement depends on reinforcement spacing, configuration, volumetric ratio, and axial load level. In UHPC, the presence of fibers may further improve post-cracking and fracture behavior by bridging cracks and transferring tensile stresses. However, fiber reinforcement should not be considered a complete substitute for appropriate transverse reinforcement and seismic detailing.

5. SEISMIC PERFORMANCE OF INDIVIDUAL STRUCTURAL COMPONENTS

The seismic performance of individual structural components is a critical aspect of evaluating the applicability of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) in high-rise reinforced concrete (RC) buildings. The behavior of beams, columns, beam-column joints, shear walls, coupling beams, core walls, and slab-column connections directly influences the overall seismic response and failure mechanism of a building. Although HSC and UHPC provide superior strength and durability, their response under reversed cyclic loading depends on several factors, including reinforcement detailing, axial load, confinement, fiber content, member geometry, and loading history. Therefore, component-level studies provide an essential basis for understanding how the improved material properties of HSC and UHPC translate into structural seismic performance.

5.1 HSC/UHPC Beams

5.1.1 Flexural and Shear Behavior

HSC and UHPC beams generally exhibit higher flexural and shear strength than beams constructed with conventional concrete. The increased compressive strength improves the compression-zone capacity, while the enhanced tensile and post-cracking properties of UHPC can improve resistance to crack propagation. In UHPFRC beams, fibers contribute to tensile stress transfer across cracks and may increase both flexural strength and shear resistance. However, the high strength of the concrete should be accompanied by appropriate reinforcement detailing to prevent brittle shear failure before the development of the intended flexural mechanism.

5.1.2 Ductility and Plastic Hinge Behavior

Under seismic loading, beams are expected to develop stable plastic hinges and dissipate energy through repeated flexural deformation. The ductility of HSC beams may be lower than that of conventional concrete beams if the high-strength matrix undergoes brittle compression failure. UHPC and UHPFRC can improve post-cracking behavior and fracture resistance, but the overall ductility remains dependent on reinforcement ratio and structural detailing. An appropriate balance between concrete strength and reinforcement is therefore necessary to ensure that plastic hinges form in the desired regions and remain stable under repeated load reversals.

5.1.3 Crack Development and Reinforcement Effects

Crack patterns in HSC and UHPC beams are influenced by concrete strength, reinforcement ratio, fiber content, and loading conditions. UHPC can limit crack width and distribute cracking more uniformly, particularly when fibers are incorporated. However, excessive reinforcement may shift the failure mechanism toward compression-controlled behavior, while insufficient reinforcement may result in premature tensile failure. Therefore, reinforcement ratio is a critical parameter in achieving the required balance between strength and ductility. Under repeated cyclic loading, stiffness and strength degradation may occur because of crack development, reinforcement yielding, bond deterioration, and concrete damage. Fiber reinforcement can reduce crack localization and delay degradation, although its effectiveness depends on fiber characteristics and distribution.

5.2 HSC/UHPC Columns

5.2.1 Axial Load and Confinement Effects

Columns in high-rise buildings are subjected to substantial axial loads in addition to bending and shear demands generated during earthquakes. The axial load ratio significantly influences the seismic response of HSC and UHPC columns. High axial compression can increase flexural strength but may reduce deformation capacity and accelerate concrete crushing. Adequate confinement is therefore essential to improve the post-peak behavior and delay compression failure. Transverse reinforcement provides confinement to the core concrete and helps maintain structural integrity during large cyclic deformations.

5.2.2 Reinforcement and Plastic Hinge Formation

The amount and arrangement of longitudinal and transverse reinforcement significantly influence column performance. Longitudinal reinforcement contributes to flexural strength and ductility, while transverse reinforcement provides confinement and restrains the buckling of longitudinal bars. Under seismic loading, plastic hinges are generally expected to form at the column ends in accordance with the intended capacity design strategy. However, excessive axial load or inadequate confinement may lead to premature crushing and axial failure. UHPC may improve the strength and durability of columns, but appropriate seismic detailing remains necessary to ensure adequate deformation capacity.

5.2.3 P–M Interaction and Failure Mechanisms

The combined effects of axial force and bending moment are commonly evaluated using axial load–moment interaction relationships. HSC and UHPC columns can provide higher load-carrying capacity within the P–M interaction domain, allowing smaller column sections in high-rise buildings. Nevertheless, increased strength may be accompanied by reduced deformation capacity if the column is subjected to high axial compression. During severe cyclic loading, crushing of concrete, buckling of longitudinal reinforcement, and loss of axial load-carrying capacity are critical failure mechanisms. Therefore, column design must ensure a stable flexural response and prevent brittle axial or shear failure.

5.3 Beam-Column Joints

5.3.1 Joint Shear and Bond Behavior

Beam-column joints are critical regions in moment-resisting RC frames because they transfer forces between beams and columns during seismic loading. The joint region is subjected to high shear stresses and repeated stress reversals, which can cause diagonal cracking and degradation of strength. HSC and UHPC can improve joint shear strength because of their higher compressive and tensile capacities. However, the dense and strong matrix does not eliminate the possibility of bond-slip or anchorage failure of reinforcement passing through the joint.

5.3.2 Joint Cracking and Panel-Zone Behavior

Cyclic loading can produce diagonal cracking within the joint panel zone, followed by stiffness and strength degradation. UHPC and UHPFRC may improve crack control and reduce crack width through their superior tensile and fiber-bridging characteristics. Nevertheless, the interaction between concrete strength, reinforcement anchorage, bond behavior, and joint confinement must be carefully considered. The strong-column/weak-beam principle remains essential to ensure that plastic hinges develop in beams rather than in columns or joints, thereby promoting a desirable and ductile global failure mechanism.

5.3.3 Types of Beam-Column Joints

The seismic behavior of interior, exterior, and corner beam-column joints differs because of variations in reinforcement anchorage and force transfer mechanisms. Interior joints generally experience complex bidirectional force transfer, while exterior and corner joints may be more vulnerable to anchorage and bond-related failures. The application of HSC and UHPC can improve the strength and crack resistance of these joints, but their effectiveness depends on reinforcement detailing and the ability of the joint to maintain stable cyclic behavior.

5.4 Shear Walls

5.4.1 Flexural and Shear Behavior

Shear walls are among the primary lateral load-resisting elements in high-rise RC buildings. Their seismic behavior is governed by the interaction of flexure, shear, axial load, and overturning effects. HSC and UHPC can enhance the strength and stiffness of shear walls, potentially allowing thinner wall sections and more efficient structural systems. However, excessive stiffness and strength should not compromise the required deformation capacity. Shear failure, particularly diagonal compression failure, must be prevented because it is generally more brittle than flexural failure.

5.4.2 Boundary Elements and Ductility

Boundary elements are critical for resisting high compressive and tensile stresses generated near the ends of shear walls during seismic response. HSC and UHPC can provide increased compressive capacity in these regions, but adequate confinement and reinforcement detailing are required to achieve ductile behavior. The ductility and drift capacity of a wall depend on its geometry, axial load, reinforcement ratio, boundary confinement, and failure mechanism. Properly designed walls should develop stable flexural plasticity while avoiding premature shear or compression failure.

5.5 Coupling Beams

5.5.1 Conventional and Diagonally Reinforced Coupling Beams

Coupling beams connect adjacent shear walls and play an important role in the seismic behavior of coupled wall systems. Conventional coupling beams may experience high shear demands and diagonal cracking, which can result in rapid degradation under cyclic loading. Diagonally reinforced coupling beams are commonly used to improve shear resistance and deformation capacity by providing a more direct load-transfer mechanism. Their seismic performance depends on reinforcement configuration, concrete strength, geometry, and cyclic loading conditions.

5.5.2 UHPC and Fiber-Reinforced Coupling Systems

UHPC and UHPFRC offer potential advantages for coupling beams because of their high shear strength, tensile resistance, and crack-bridging capability. Fiber reinforcement can improve crack distribution and post-cracking behavior, potentially enhancing energy dissipation and cyclic stability. The use of UHPC may also allow more compact coupling beam sections and improve constructability in heavily reinforced regions. However, further research is required to establish reliable design procedures for UHPC coupling beams subjected to severe seismic loading.

6. HSC AND UHPC IN HIGH-RISE RC BUILDING SYSTEMS

The application of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) in high-rise reinforced concrete (RC) buildings has significant potential to improve structural efficiency, durability, and load-carrying capacity. As building height increases, the demands imposed on columns, shear walls, core systems, and lateral load-resisting elements become increasingly severe. HSC and UHPC can address some of these challenges by providing higher strength and stiffness with reduced member dimensions. However, their application also modifies the mass, stiffness, dynamic characteristics, and seismic response of the overall structural system. Therefore, their performance should be evaluated at the building scale rather than only at the material or component level.

6.1 Structural Systems Used in High-Rise Buildings

6.1.1 Moment-Resisting Frames and Shear Wall Systems

Moment-resisting frames are designed to resist lateral loads primarily through the flexural action of beams and columns. They can provide significant ductility when properly detailed but may require large member dimensions in very tall buildings. Shear wall systems, in contrast, provide greater lateral stiffness and are widely used in high-rise construction to control lateral displacement and interstory drift. The use of HSC and UHPC in beams, columns, and shear walls can increase load-carrying capacity and allow more efficient structural dimensions. However, adequate ductility and seismic detailing remain essential to prevent brittle failure.

6.1.2 Dual, Core-Wall, Tube, and Outrigger Systems

Dual systems combine moment-resisting frames with shear walls or core walls, allowing the two systems to share lateral seismic demands. Core-wall systems use a central structural core to resist a major portion of lateral forces and overturning moments. Tube systems utilize the perimeter of the building as an efficient lateral load-resisting mechanism, while outrigger systems connect the central core to perimeter columns to improve lateral stiffness and reduce overturning response. HSC and UHPC can be particularly beneficial in these systems because their high strength enables efficient columns, walls, and core elements. Nevertheless, the interaction between material properties and global structural behavior must be carefully considered under seismic loading.

6.2 Role of HSC/UHPC in High-Rise Construction

6.2.1 Structural Efficiency and Reduced Member Dimensions

The high compressive strength of HSC and UHPC allows heavily loaded structural members to carry greater forces with smaller cross-sectional dimensions. This is particularly advantageous for lower-story columns and core walls in high-rise buildings, where gravity loads accumulate over multiple floors. Smaller structural members can increase usable floor area and provide greater architectural flexibility. In addition, reduced member dimensions may decrease reinforcement congestion, particularly in highly stressed beam-column joints and heavily reinforced columns.

6.2.2 Reduction in Structural Weight and Improved Durability

The reduction in member size can potentially reduce the total volume of concrete and structural dead weight. A lighter structural system may experience lower seismic inertia forces, although the actual effect depends on the complete dynamic response of the building. UHPC also provides very low permeability and improved resistance to environmental deterioration, which can enhance the long-term durability of high-rise structures. These benefits may contribute to lower maintenance requirements and improved service life.

6.2.3 Construction Efficiency

HSC and UHPC can improve construction efficiency by reducing the dimensions of structural members and potentially simplifying heavily congested reinforcement regions. UHPC may also facilitate thinner structural sections and improved connection performance. However, specialized mixing, placement, curing, quality control, and skilled labor may be required, particularly for UHPC. Therefore, the overall construction efficiency must be evaluated by considering both the structural advantages and the practical requirements associated with advanced concrete materials.

6.3 High-Rise Building Load Path

6.3.1 Gravity and Lateral Load Transfer

The load path of a high-rise RC building defines how gravity and lateral loads are transferred through the structural system. Gravity loads from floors and occupants are transferred through slabs and beams to columns and walls and ultimately to the foundation. HSC and UHPC can improve this load path by providing higher capacity in heavily loaded columns and walls, thereby allowing more efficient structural sections.

Lateral loads generated by wind and earthquakes are transferred through floor diaphragms to the designated lateral load-resisting elements, such as moment frames, shear walls, or core systems. During an earthquake, the diaphragm action distributes inertial forces among these elements according to their relative stiffness and strength. Therefore, changes in stiffness caused by the use of HSC and UHPC can influence the distribution of seismic forces throughout the building.

6.3.2 Seismic Load Path and Foundation Interaction

The seismic load path begins with earthquake-induced inertial forces generated throughout the building mass and continues through floor diaphragms to the vertical lateral load-resisting system. These forces are eventually transferred to the foundation and supporting soil. In high-rise buildings, significant overturning moments and vertical force variations may develop during strong earthquakes. Consequently, foundation flexibility and soil-structure interaction can influence the overall seismic response. The use of HSC and UHPC may modify the stiffness and mass distribution of the superstructure, making consideration of the complete load path essential for accurate seismic evaluation.

7. SEISMIC PERFORMANCE EVALUATION METHODS

The seismic performance evaluation of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) requires a combination of experimental investigation, numerical simulation, constitutive modeling, and nonlinear structural analysis. Since the seismic response of high-rise reinforced concrete (RC) buildings involves complex interactions among material nonlinearity, structural deformation, cyclic degradation, and dynamic effects, no single evaluation method is sufficient to fully characterize performance. Experimental methods provide direct evidence of material and structural behavior, whereas numerical approaches enable the simulation of complex structural systems and earthquake scenarios. The integration of these methods provides a comprehensive framework for assessing the seismic suitability of HSC and UHPC.

7.1 Experimental Methods

7.1.1 Material-Level and Cyclic Component Tests

Material-level tests are fundamental for determining the mechanical properties required for seismic analysis of HSC and UHPC. These tests commonly investigate compressive strength, tensile behavior, fracture energy, cyclic stress-strain response, and post-peak behavior. For UHPFRC, fiber bridging and post-cracking tensile performance are particularly important parameters. The experimental results obtained at the material level provide the basic input parameters for constitutive models used in nonlinear numerical simulations.

Cyclic component tests are conducted on structural members such as beams, columns, beam-column joints, shear walls, and coupling beams. These experiments provide information regarding hysteretic response, stiffness degradation, strength deterioration, ductility, crack development, energy dissipation, and failure mechanisms. Quasi-static cyclic tests are widely used because they can reproduce repeated displacement reversals representative of earthquake-induced structural deformation while allowing detailed observation of damage progression.

7.1.2 Full-Scale and Large-Scale Testing

Full-scale or large-scale experimental testing provides a more realistic representation of structural behavior than small-scale material or component tests. Such tests can capture the interaction among multiple structural components and the influence of realistic reinforcement detailing and construction practices. However, full-scale testing of high-rise structural systems is expensive and technically demanding. Consequently, large-scale experimental programs are often combined with numerical simulations to extend the findings to complete building systems.

7.2 Numerical Methods

7.2.1 Finite Element and Fiber-Based Modeling

Finite Element Analysis (FEA) is widely used to simulate the nonlinear behavior of HSC and UHPC structural components and complete building systems. Detailed finite element models can represent concrete cracking, crushing, reinforcement yielding, contact behavior, and bond effects. Such models are particularly useful for investigating local failure mechanisms that may be difficult to observe experimentally.

Fiber-based modeling provides an efficient alternative for structural analysis by dividing beam-column sections into discrete fibers representing concrete and reinforcement. The nonlinear stress-strain behavior of each fiber can be integrated to determine the overall sectional response. This approach is particularly suitable for nonlinear analysis of high-rise RC frames, columns, and walls because it can capture distributed material nonlinearity while maintaining reasonable computational efficiency.

7.2.2 Macro-Element and Plastic Hinge Models

Macro-element models represent structural components using simplified formulations that capture the dominant global response without explicitly modeling local material behavior. These models are computationally efficient and suitable for analyzing complete high-rise buildings. Plastic hinge models concentrate inelastic deformation at predefined locations, generally near the ends of beams and columns, and are commonly used in nonlinear structural analysis.

Distributed plasticity models, in contrast, allow nonlinear behavior to develop over a finite length or throughout the structural member. They can provide a more realistic representation of gradual damage accumulation and plastic hinge development. The choice between concentrated plasticity and distributed plasticity depends on the required level of accuracy, computational resources, and objectives of the analysis.

8. PERFORMANCE EVALUATION PARAMETERS

The seismic performance of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) in high-rise reinforced concrete (RC) buildings should be evaluated using a comprehensive set of parameters that capture strength, deformation, energy dissipation, damage, global structural response, and post-earthquake resilience. No single parameter can adequately describe the seismic performance of an advanced concrete structural system because earthquake response involves complex interactions between local material behavior and global structural dynamics. Therefore, a comparative evaluation framework incorporating multiple performance indicators is necessary to distinguish the advantages and limitations of HSC and UHPC relative to conventional concrete.

8.1 Strength-Based Parameters

8.1.1 Load-Carrying Capacity

Strength-based parameters provide a fundamental measure of the ability of structural components and complete buildings to resist seismic demands. Peak load represents the maximum load sustained during testing, whereas ultimate load generally refers to the maximum or critical load associated with the ultimate capacity of the structural system. In the case of HSC and UHPC, the high compressive strength of the concrete can significantly increase the load-carrying capacity of columns, shear walls, beams, and connections. However, strength enhancement should be assessed alongside the corresponding failure mode to ensure that increased capacity does not result in undesirable brittle behavior.

8.1.2 Flexural and Shear Strength

Flexural strength is particularly important for evaluating beams, columns, and shear walls designed to develop ductile flexural mechanisms. Shear strength is equally critical because shear failure is generally brittle and can occur suddenly without sufficient warning. UHPC and UHPFRC may provide significant improvements in shear and flexural resistance due to their high matrix strength and, in fiber-reinforced systems, enhanced tensile and crack-bridging capacity. Comparative assessment should therefore examine whether the increase in strength is accompanied by adequate deformation and energy dissipation capacity.

8.2 Deformation-Based Parameters

8.2.1 Interstory Drift and Maximum Displacement

Deformation-based parameters are essential for evaluating the seismic performance of high-rise buildings because earthquake damage is often strongly related to lateral deformation. The interstory drift ratio represents the relative lateral displacement between two adjacent floors normalized by story height and is widely used to assess both structural and nonstructural damage. Maximum displacement provides an overall measure of the lateral response of the building. HSC and UHPC may reduce displacement demands because of their higher stiffness; however, increased stiffness can also alter the dynamic characteristics and acceleration response of the building.

8.2.2 Ductility, Plastic Rotation, and Drift Concentration

The ductility ratio represents the ability of a structure or component to undergo inelastic deformation beyond its yield point while maintaining adequate strength. Plastic rotation measures the localized inelastic deformation developed in plastic hinge regions and is particularly relevant for assessing the seismic behavior of beams, columns, and walls. Drift concentration indicates whether deformation is distributed throughout the building or localized within specific stories. Excessive concentration can lead to soft-story mechanisms and localized structural collapse. Therefore, the evaluation of HSC and UHPC systems should consider not only the magnitude of deformation but also its distribution and stability.

8.3 Energy-Based Parameters

8.3.1 Hysteretic and Cumulative Energy Dissipation

Energy-based parameters provide important information about the ability of a structural system to absorb and dissipate earthquake-induced energy. Hysteretic energy is represented by the area enclosed within the load-displacement or stress-strain hysteresis loops during cyclic loading. A larger and more stable hysteretic response generally indicates greater energy dissipation capacity. Cumulative energy dissipation accounts for the energy dissipated over multiple cycles and provides an indication of the structural system's ability to sustain repeated seismic demands without severe degradation.

8.3.2 Equivalent Viscous Damping

Equivalent viscous damping provides a simplified measure of the energy dissipation associated with nonlinear hysteretic behavior. It is useful for comparing the seismic response of conventional concrete, HSC, UHPC, and UHPFRC systems. Although UHPC may exhibit superior strength and fracture resistance, the overall equivalent damping depends on the structural system, reinforcement detailing, cracking behavior, and hysteretic stability. Therefore, energy-based evaluation should be conducted together with strength and deformation parameters to obtain a balanced assessment of seismic performance.

8.4 Damage-Based Parameters

8.4.1 Crack Width and Crack Density

Cracking is one of the primary indicators of structural damage under seismic loading. Crack width provides information regarding the severity of local damage and potential durability implications, while crack density reflects the extent and distribution of cracking throughout a structural component. UHPC and UHPFRC generally demonstrate improved crack control compared with conventional concrete due to their dense matrix and fiber-bridging mechanisms. However, the distribution and progression of cracks under repeated seismic loading must be carefully evaluated because localized cracking may still lead to significant stiffness degradation.

8.4.2 Damage Index and Concrete Spalling

Damage indices provide quantitative measures of structural deterioration by combining parameters such as deformation, stiffness degradation, strength loss, or cumulative energy dissipation. Such indices can be used to compare the progression of damage among different concrete systems. Concrete spalling is another important indicator, particularly in compression zones and plastic hinge regions. Although HSC and UHPC may provide improved surface durability and strength, high-strength concrete can experience significant localized crushing or spalling under severe compression if adequate confinement is not provided.

8.4.3 Reinforcement Buckling

Buckling of longitudinal reinforcement is an important failure mechanism in heavily loaded RC columns and plastic hinge regions subjected to large cyclic deformations. It can lead to rapid deterioration of strength and axial load-carrying capacity. The use of appropriate transverse reinforcement and adequate confinement is essential to delay reinforcement buckling. Therefore, reinforcement stability should be considered when evaluating the seismic performance of HSC and UHPC structural components.

9. CONCLUSION

The present review critically examines the performance of High-Strength Concrete (HSC) and Ultra-High-Performance Concrete (UHPC) in high-rise reinforced concrete (RC) buildings subjected to seismic loading. The review indicates that HSC and UHPC offer significant advantages over conventional concrete in terms of compressive strength, stiffness, durability, crack resistance, and structural efficiency. Their application can facilitate reduced column and wall dimensions, increased usable floor area, improved load-carrying capacity, and enhanced durability, which are particularly beneficial for high-rise construction. However, increased material strength does not inherently guarantee superior seismic performance. The seismic behavior of these materials is strongly influenced by ductility, confinement, cyclic degradation, energy dissipation, crack propagation, and reinforcement detailing. HSC may exhibit brittle compression behavior and limited deformation capacity when inadequately confined, whereas UHPC and UHPFRC demonstrate promising post-cracking performance through improved tensile resistance and fiber-bridging mechanisms. At the building scale, changes in structural stiffness and mass can significantly influence natural periods, higher-mode effects, P–Δ response, interstory drift, and seismic demand. The review further highlights that experimental studies are predominantly concentrated on material properties and individual structural components, while full-scale evidence for UHPC-based high-rise systems remains comparatively limited. Therefore, future research should focus on integrated experimental and numerical investigations, reliable constitutive models, performance-based seismic design, system-level validation, and resilience-oriented assessment. Overall, HSC and UHPC represent promising technologies for improving the efficiency, durability, and seismic resilience of high-rise RC buildings, provided that their application is supported by appropriate ductile detailing and comprehensive structural evaluation.

9.1. Limitations of the Review

This review has certain limitations that should be acknowledged when interpreting its findings. First, the available literature on the seismic performance of UHPC and UHPFRC in complete high-rise RC buildings remains relatively limited compared with research on conventional concrete and individual structural components. Second, significant variations exist among published studies in terms of material composition, fiber type and volume, reinforcement detailing, loading protocols, structural dimensions, and experimental conditions, which restrict direct quantitative comparison. Third, differences in seismic design codes, analytical approaches, constitutive models, and performance criteria may influence reported results. The review also relies primarily on published research and may therefore be affected by publication bias and the limited availability of negative or inconclusive findings. Furthermore, the long-term effects of creep, shrinkage, durability deterioration, and repeated seismic events on UHPC-based high-rise structures remain insufficiently investigated. These limitations highlight the need for standardized testing procedures, large-scale experiments, validated numerical models, and comprehensive building-level studies.

REFERENCES

[1] H. Bechtoula, S. Kono, and F. Watanabe, “Seismic performance of high strength reinforced concrete columns,” Structural Engineering and Mechanics, vol. 31, no. 6, pp. 697–714, 2009, doi: 10.12989/sem.2009.31.6.697.

[2] C. Jin, Z. Pan, S. Meng, and Z. Qiao, “Seismic behavior of shear-critical reinforced high-strength concrete columns,” Journal of Structural Engineering, vol. 141, no. 8, Art. no. 04014198, 2015, doi: 10.1061/(ASCE)ST.1943-541X.0001167.

[3] C. P. Jin, Z. Pan, S. Meng, and Z. Qiao, “Seismic behavior of high-strength concrete columns reinforced with high-strength steel bars,” Engineering Structures, vol. 218, Art. no. 110861, 2020, doi: 10.1016/j.engstruct.2020.110861.

[4] A. Taheri, A. S. Moghadam, and A. A. Tasnimi, “Critical factors in displacement ductility assessment of high-strength concrete columns,” International Journal of Advanced Structural Engineering, vol. 9, pp. 325–340, 2017, doi: 10.1007/s40091-017-0169-6.

[5] Z. Z. Bai and F. T. K. Au, “Flexural ductility design of high-strength concrete columns,” The Structural Design of Tall and Special Buildings, vol. 22, pp. 92–115, 2013, doi: 10.1002/tal.662.

[6] A. Martirossyan and Y. Xiao, “Flexural-shear behavior of high-strength concrete short columns,” Earthquake Spectra, vol. 17, no. 4, 2001, doi: 10.1193/1.1423656.

[7] B. Li and C. L. Leong, "Experimental and numerical investigations of the seismic behavior of high-strength concrete beam-column joints with column axial load," Journal of Structural Engineering, vol. 141, no. 9, Art. no. 04014191, 2015, doi: 10.1061/(ASCE)ST.1943-541X.0001191.

[8] S. A. Attaalla and M. S. Agbabian, "Performance of interior beam-column joints cast from high strength concrete under seismic loads," Journal of Earthquake Engineering, vol. 7, no. 2, 2004, doi: 10.1260/1369433041211093.

[9] S. Sugano, T. Nagashima, H. Kimura, and A. Ichikawa, "Experimental study on seismic behavior of beam-column joints using high-strength concrete and high-strength steel bar," Journal of Structural and Construction Engineering (Transactions of AIJ), no. 423, pp. 147–158, 1991, doi: 10.3130/aijsx.423.0_147.

[10] S. Sugano, T. Nagashima, H. Kimura, A. Tamura, and A. Ichikawa, "Experimental studies on seismic behavior of reinforced concrete members of high-strength concrete," ACI Special Publication, vol. 121, pp. 61–88, 1990, doi: 10.14359/2791.

[11] X. Nadir, A. Y. Ali, A. Jawdhari, M. M. A. Kadhim, et al., "Cyclic behavior of UHPC corner beam-column joints under bi-directional bending," Structures, 2024, Art. no. 105857, doi: 10.1016/j.istruc.2024.105857.

[12] X. Cai, L. Taerwe, and Y. Yuan, "Hysteretic behavior of UHPC beam-column joints after fire exposure," Fire Safety Journal, vol. 117, Art. no. 102987, 2020, doi: 10.1016/j.firesaf.2020.102987.

[13] X. Guohua, H. Wang, and E. O. Ozbulut, "Seismic behavior of multiple reinforcement, high-strength concrete columns: Experimental and theoretical analysis," Earthquake Engineering and Engineering Vibration, vol. 21, no. 2, pp. 359–375, 2022, doi: 10.1007/s11803-022-2095-2.

[14] S. Sugano, T. Nagashima, H. Kimura, and A. Ichikawa, "Experimental study on seismic behavior of beam-column joints using high-strength concrete and high-strength steel bar," Journal of Structural and Construction Engineering, no. 423, pp. 147–158, 1991, doi: 10.3130/aijsx.423.0_147.

[15] J. Su, X. Tan, and F. Lu, "Seismic behavior of exterior beam–column joints in reinforced ultra-high performance concrete frames: An experimental and theoretical study," Journal of Building Engineering, vol. 126, Art. no. 116288, 2026, doi: 10.1016/j.jobe.2026.116288.

[16] X. Hu and W. Xue, "Seismic performance of ultra-high performance concrete beam-column joints reinforced with glass fiber-reinforced polymer rebars under cyclic loading," Journal of Building Engineering, vol. 129, Art. no. 116763, 2026, doi: 10.1016/j.jobe.2026.116763.

[17] V. C. Mai, V. T. Nguyen, and X. D. Nguyen, "Seismic enhancement of RC exterior beam-column joints using Ultra High Performance Concrete layers," Journal of Applied Science and Engineering, vol. 29, no. 5, pp. 1193–1202, 2025, doi: 10.6180/jase.202605_29(5).0015.

[18] X. Tian, Z. Fang, and Y. Shao, "Flexural behavior and design of prestressed ultra-high performance concrete (UHPC) beams: Failure mode and ductility," 2024, doi: 10.48550/arXiv.2411.01113.

[19] H. Ousalem, H. Takatsu, Y. Ishikawa, and H. Kimura, "Seismic testing and performance of precast high-strength concrete beam-column joints subjected to high axial tension," Journal of Advanced Concrete Technology, vol. 7, no. 2, pp. 195–204, 2009, doi: 10.3151/jact.7.195.

[20] P. Alaee and B. Li, "High-strength concrete interior beam-column joints with high-yield-strength steel reinforcements," Journal of Structural Engineering, vol. 143, no. 7, 2017, doi: 10.1061/(ASCE)ST.1943-541X.0001773.

[21] K. Shi, M. Zhang, T. Zhang, P. Li, J. Zhu, and L. Li, "Seismic performance of steel fiber reinforced high-strength concrete beam-column joints," Materials, vol. 14, no. 12, Art. no. 3235, 2021, doi: 10.3390/ma14123235.

[22] S. A. Attaalla and M. S. Agbabian, "Performance of interior beam-column joints cast from high strength concrete under seismic loads," Journal of Earthquake Engineering, vol. 7, no. 2, 2004, doi: 10.1260/1369433041211093.

[23] J. Zhang, B. Zhang, X. Rong, and C. Ding, "Experimental research on seismic behavior of high strength bar concrete beam-column joints reinforced by steel fiber," Journal of Northeastern University Natural Science, vol. 41, no. 10, pp. 1465–1475, 2020, doi: 10.12068/j.issn.1005-3026.2020.10.016.

[24] S. Sugano, T. Nagashima, H. Kimura, and A. Ichikawa, "Experimental study on seismic behavior of beam-column joints using high-strength concrete and high-strength steel bar," Journal of Structural and Construction Engineering, no. 423, pp. 147–158, 1991, doi: 10.3130/aijsx.423.0_147.

[25] B. Li and C. L. Leong, "Experimental and numerical investigations of the seismic behavior of high-strength concrete beam-column joints with column axial load," Journal of Structural Engineering, vol. 141, no. 9, 2015, doi: 10.1061/(ASCE)ST.1943-541X.0001191.

[26] X. Cai, L. Taerwe, and Y. Yuan, "Hysteretic behavior of UHPC beam-column joints after fire exposure," Fire Safety Journal, vol. 117, Art. no. 102987, 2020, doi: 10.1016/j.firesaf.2020.102987.

[27] X. Nadir et al., "Cyclic behavior of UHPC corner beam-column joints under bi-directional bending," Structures, 2024, Art. no. 105857, doi: 10.1016/j.istruc.2024.105857.

[28] V. C. Mai, V. T. Nguyen, and X. D. Nguyen, "Seismic enhancement of RC exterior beam-column joints using Ultra High Performance Concrete layers," Journal of Applied Science and Engineering, vol. 29, no. 5, pp. 1193–1202, 2025, doi: 10.6180/jase.202605_29(5).0015.

[29] X. Hu and W. Xue, "Seismic performance of ultra-high performance concrete beam-column joints reinforced with glass fiber-reinforced polymer rebars under cyclic loading," Journal of Building Engineering, 2026, Art. no. 116763, doi: 10.1016/j.jobe.2026.116763.

[30] J. Su, X. Tan, and F. Lu, "Seismic behavior of exterior beam–column joints in reinforced ultra-high performance concrete frames: An experimental and theoretical study," Journal of Building Engineering, 2026, Art. no. 116288, doi: 10.1016/j.jobe.2026.116288.

[31] "Seismic performance of squat UHPC shear walls subjected to high-compression shear combined cyclic load," Engineering Structures, vol. 276, Art. no. 115369, 2023, doi: 10.1016/j.engstruct.2022.115369.

[32] C. Jin, Z. Pan, S. Meng, and Z. Qiao, "Seismic behavior of shear-critical reinforced high-strength concrete columns," Journal of Structural Engineering, vol. 141, no. 8, 2015, doi: 10.1061/(ASCE)ST.1943-541X.0001167.

[33] C. P. Jin, Z. Pan, S. Meng, and Z. Qiao, "Seismic behavior of high-strength concrete columns reinforced with high-strength steel bars," Engineering Structures, vol. 218, Art. no. 110861, 2020, doi: 10.1016/j.engstruct.2020.110861.

[34] H. Bechtoula, S. Kono, and F. Watanabe, "Seismic performance of high strength reinforced concrete columns," Structural Engineering and Mechanics, vol. 31, no. 6, pp. 697–714, 2009, doi: 10.12989/sem.2009.31.6.697.

[35] A. Taheri, A. S. Moghadam, and A. A. Tasnimi, "Critical factors in displacement ductility assessment of high-strength concrete columns," International Journal of Advanced Structural Engineering, vol. 9, pp. 325–340, 2017, doi: 10.1007/s40091-017-0169-6.

[36] Z. Z. Bai and F. T. K. Au, "Flexural ductility design of high-strength concrete columns," The Structural Design of Tall and Special Buildings, vol. 22, pp. 92–115, 2013, doi: 10.1002/tal.662.

[37] A. Martirossyan and Y. Xiao, "Flexural-shear behavior of high-strength concrete short columns," Earthquake Spectra, vol. 17, no. 4, 2001, doi: 10.1193/1.1423656.

[38] S. Sugano, T. Nagashima, H. Kimura, A. Tamura, and A. Ichikawa, "Experimental studies on seismic behavior of reinforced concrete members of high-strength concrete," ACI Special Publication, vol. 121, pp. 61–88, 1990, doi: 10.14359/2791.

[39] B. Li and C. L. Leong, "Seismic performance of high-strength concrete structural members and joints," Journal of Structural Engineering, relevant research on cyclic behavior and high-strength RC systems.