

Article

A Novel UHPC-NC Composite Column Frame Structure: Design and Seismic Performance Investigation

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Abstract

Existing studies have demonstrated that insufficient horizontal deformation capacity of columns under high axial compression ratios constitutes a key factor leading to seismic damage in ordinary concrete frame structures. This paper proposes a novel framed structure incorporating composite columns by combining ultra-high performance concrete (UHPC), which exhibits excellent mechanical properties, with normal concrete (NC). The design concept maintains the overall mechanical performance of the composite column frame structure while significantly reducing the lateral stiffness when the composite columns are configured in a “split-column form.” For instance, the lateral stiffness of ZH-5 in the “split-column form” is only one-tenth of that of ZT-1 in its initial state, leading to a substantial enhancement in horizontal deformation capacity. This design approach maintains the overall mechanical performance of the composite column frame structure while significantly enhancing its horizontal deformation capacity by reducing lateral stiffness through the “split-column” configuration. Using the ABAQUS finite element software 2021, a finite element model of a multi-story frame column structure was developed. Research findings indicate that the frame structure utilizing UHPC-NC composite columns exhibits reduced tensile damage, lower peak and plastic displacements, and a relatively smaller inter-story drift angle. Specifically, the plastic drift angle of the UHPC-NC composite column frame structure from the first to the fourth story is 5% to 31% smaller than that of the conventional reinforced concrete column frame structure. The novel UHPC-NC composite column frame structure demonstrates superior seismic performance.

Keywords: UHPC-NC composite columns; frame structures; seismic performance; lateral stiffness; dynamic time history analysis method



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1. Introduction

Earthquakes are sudden and highly destructive natural disasters that pose significant threats to human life and property safety. China is situated at the junction of the Eurasian and Indian Ocean tectonic plates, making it a high-seismic-activity zone; thus, the severity of earthquake disasters has become one of the fundamental national conditions of our country. In existing high-rise frame column structures, due to the axial compression ratio limitations of the bottom frame columns, the cross-sections of the bottom columns are relatively large, and the shear span ratios are relatively small; therefore bottom frame columns can be considered short columns (referred to as RC short columns). RC short columns

exhibit substantial horizontal lateral stiffness but poor horizontal deformation capacity and seismic performance. Scholars have attempted to improve the seismic performance of RC columns through various methods, such as increasing stirrup density [1], using core columns [2], and employing split columns [3]. Additionally, scholars have proposed the use of high-strength materials to reinforce RC columns [4–6]. Research indicates that the plastic hinge zones of RC short columns are prone to damage, and the local application of stainless steel mesh-reinforced ultra-high-performance concrete (UHPC) jackets in the plastic hinge zones has been suggested [7]. However, these methods are primarily based on the enhancement of ordinary concrete and struggle to simultaneously address both the strength and deformation capacity (stiffness) of short columns.

Ultra-High Performance Concrete (UHPC) is a fiber-reinforced cementitious composite material [8,9], which exhibits exceptional mechanical properties, superior compressive and tensile strength, remarkable toughness, and enhanced durability compared to Normal Concrete (NC) [10]. The application of UHPC in strengthening Reinforced Concrete (RC) beams [11–14] and columns [5] significantly enhances the load-bearing capacity and improves the failure mode of the specimens. Bassam, A., et al. [15] investigated the bond strength between UHPC and NC substrates, revealing that UHPC and NC substrates exhibit excellent interlocking relationships, with test results demonstrating that the bond strength exceeds that of the NC substrate. Yuan, S., et al. [16] proposed a deck concept utilizing the NC-UHPC composite structural system and conducted relevant tests, which indicated that non-reinforced NC-UHPC beams significantly improved the strength and stiffness of the beams. Ibrahim Y. Hakeem, et al. [17] studied UHPC-reinforced hybrid beams, demonstrating that the intentionally designed uneven surface between the NC and UHPC layers provides acceptable interface shear strength, ensuring composite performance under load. UHPC offers the potential for designing hybrid structural flexural members in NC-UHPC structures, where UHPC can replace passive reinforcement to achieve the required flexural strength. In summary, UHPC and NC exhibit excellent interfacial bonding effects, creating favorable conditions for the formation of composite columns with superior mechanical performance.

To investigate the seismic performance of UHPC columns, scholars have conducted relevant research. Yi Shao et al. [18] studied the seismic performance of full-scale UHPC-jacketed RC columns under high axial loads. The research findings indicate that the R/UHPC jacketing method increased the peak strength and initial stiffness of the columns by 40% to 70% and 20% to 50%, respectively. Additionally, the compressive strength of ultra-high-performance concrete (UHPC) is three to four times that of reinforced concrete [19], allowing for a significant reduction in the cross-sectional dimensions of UHPC compression members, thereby effectively reducing the seismic inertial forces of the structure. Given the superior ductility and toughness of UHPC, it significantly enhances the flexibility of compression members and exhibits excellent energy dissipation capacity [20]. Scholars have researched seismic structural design using UHPC as a replacement for normal concrete (NC) [21,22]. The studies demonstrate that replacing NC with UHPC improves the plastic deformation performance and damage tolerance of the members, increasing their displacement ductility. UHPC columns exhibit excellent ductility, energy dissipation capacity, and certain self-centering capabilities in quasi-static tests. The volume fraction of steel fibers significantly influences the failure mode of UHPC columns [23], and an appropriate volume fraction of steel fibers can markedly mitigate concrete crushing and spalling, enhancing the ductility of UHPC columns. High axial compression ratios are detrimental to the seismic performance of columns. However, in quasi-static tests of novel UHPC beam–column joints under high axial compression ratios [24], the crack width propagation in the UHPC beam–column joints was effectively controlled, showing a trend of

multiple crack development. The novel UHPC beam–column joints exhibit strong energy dissipation and seismic performance. Strengthening reinforced concrete frame columns with UHPC follows the same principles as the traditional section enlargement method in terms of structural seismic response [25]. After strengthening, the lateral stiffness of the structure increases, the inter-story drift angle significantly decreases, and the damage state of structural components under rare earthquakes is effectively managed. Compared to the traditional section enlargement method, the UHPC strengthening method can reduce the cross-sectional dimensions of frame columns by more than 30% while ensuring the same overall seismic performance, minimize the occupancy of usable space by the strengthening components, and improve on-site construction efficiency. Ultra-High Performance Concrete (UHPC) columns exhibit favorable seismic performance; however, their relatively high overall stiffness may constrain deformation capacity to some extent, which is detrimental to structural earthquake resistance. As previously established, enhancing the seismic behavior of short columns solely based on conventional concrete reinforcement makes it difficult to achieve both strength and deformability simultaneously. To address these inherent limitations, this paper proposes a composite structural system that integrates UHPC with conventional concrete, demonstrating improved seismic performance, reduced stiffness under seismic action, and enhanced deformation capacity.

Therefore, this study adopts an innovative design configuration by leveraging the superior mechanical properties of Ultra-High Performance Concrete (UHPC) in structural design, resulting in the development of a novel UHPC-Normal Concrete (NC) composite column. This structural system integrates the exceptional mechanical characteristics of UHPC with conventional concrete, significantly enhancing the energy dissipation capacity of the structure. The research addresses a critical gap in the existing literature concerning the seismic performance of UHPC-NC composite column frame structures. Furthermore, the application of UHPC-NC composite columns in seismic-resistant frame systems is investigated through dynamic time-history analysis to evaluate their seismic behavior and assess the feasibility of promoting such damping measures in frame structures. The findings provide valuable references for the practical design and implementation of UHPC-NC composite columns in engineering applications.

2. UHPC-NC Composite Column Structure and Its Lateral Stiffness

2.1. UHPC-NC Composite Column Structure

The schematic diagram of RC short columns and UHPC-NC composite columns is illustrated in Figure 1. Figure 2a depicts a reinforced concrete column referenced from a specific frame structure project [26,27], while Figure 2b presents the structural configuration of the UHPC-NC composite column. In this composite column, corner elements cross-sections are constructed using UHPC columns, either cast in place or prefabricated, with normal concrete (NC) filling the spaces between the UHPC columns. Appropriate shear connectors are employed to integrate the UHPC columns with the NC columns, forming a unified composite column. The specimen fabrication process may involve initially casting the UHPC columns at the four corners, allowing them to attain stable strength before proceeding with the casting of the normal concrete columns. Alternatively, the process can commence with the prefabrication of UHPC columns, followed by their installation and subsequent casting of the normal concrete columns.

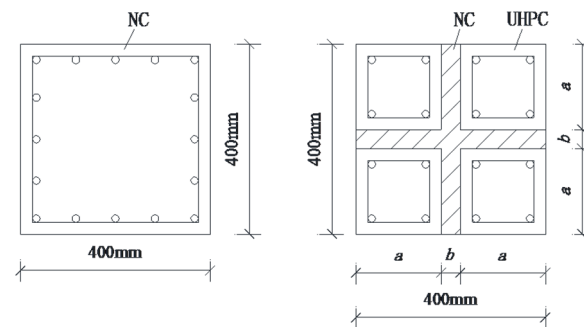


Figure 1. Schematic diagram of RC short column and UHPC-NC composite column.

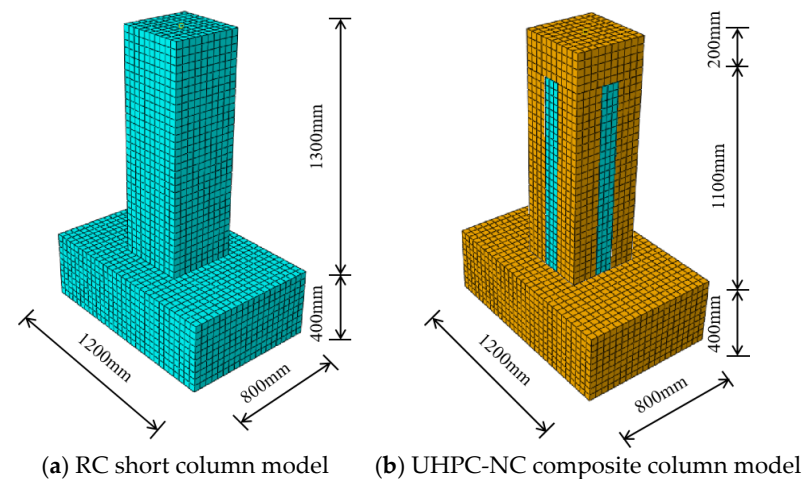


Figure 2. Schematic Diagram of RC Short Column and UHPC-NC Composite Column Model.

The UHPC-NC composite column combines the superior mechanical properties of Ultra-High Performance Concrete (UHPC) with normal concrete, significantly enhancing the energy dissipation capacity of the structure. Under low earthquake magnitudes or in the absence of earthquakes, the normal concrete within the composite column remains intact, preventing cracking or damage. This results in increased overall stiffness and improved force distribution throughout the structure. However, when an earthquake reaches a certain intensity, the normal concrete may reach or exceed its tensile or shear strength, leading to cracking or failure. At this point, the composite column transitions into a more flexible structure, which not only greatly enhances the seismic performance of the UHPC-NC column but also improves the stress distribution in the main beam and column at the top of the column.

2.2. Theoretical Analysis of Lateral Stiffness in UHPC-NC Composite Columns

Under the integral state, the UHPC-NC composite column exhibits substantial lateral stiffness. As the reinforced concrete within the composite column undergoes failure, the UHPC column continues to function, resulting in the formation of a “separated column configuration.” At this stage, the lateral stiffness of the UHPC-NC column experiences a sudden reduction, stabilizing at a level significantly lower than that of the integral UHPC-NC composite column. This phenomenon facilitates the transition of the composite structure towards a more flexible column behavior, with gradual stiffness degradation observed during the latter stages of quasi-static numerical analysis [28]. The lateral stiffness serves as a critical parameter in determining whether the UHPC-NC composite column transitions into the “separated column” configuration. This section will conduct a theoretical analysis of the lateral stiffness of UHPC-NC composite columns.

2.2.1. Overall Column Lateral Displacement Stiffness

Based on the actual conditions, the bottom end of the column is fixed while the top end is allowed to slide. A horizontal force is applied at the top of the column. According to the theoretical calculation formulas derived from material mechanics and structural mechanics, the bending displacement Δ_m and shear displacement Δ_v are induced by the horizontal load. The total lateral displacement of the column can be expressed as follows:

$$\Delta = \Delta_m + \Delta_v = \frac{FH^3}{12EI} + \frac{FH}{GA} \quad (1)$$

$$D = \frac{F}{\Delta} = \frac{12EIGA}{GAH^3 + EIH} \quad (2)$$

$$G = \frac{E}{2(1 + \mu)} \quad (3)$$

In the equation: E represents the elastic modulus of concrete, G denotes the shear modulus of concrete, and μ signifies Poisson's ratio of concrete.

2.2.2. The Lateral Stiffness of UHPC Split Columns

After the failure of reinforced concrete in tension, only the UHPC column participates in resisting lateral loads. During the elastic stage, the UHPC split column considers its bending displacement Δ_m and shear displacement Δ_v induced by lateral loads [29,30]. To facilitate quantitative analysis in the model calculations, this paper posits the following assumption: the lateral stiffness of ultra-high performance concrete (UHPC)–normal concrete (NC) composite columns and normal concrete columns within the elastic range is treated as equivalent to their lateral stiffness under plastic deformation conditions. The lateral stiffness of the split column within the elastic range can be calculated. Let Δ_{mi} and Δ_{vi} denote the bending displacement and shear displacement of the i -th split column, respectively. Consequently, the bending displacement, shear displacement, and lateral stiffness of the i -th split column can be derived as follows:

$$\Delta_{(m_i)} = \frac{H^3}{12EI_i} \quad (4)$$

$$\Delta_{v_i} = \frac{H}{GA_i} \quad (5)$$

$$D_i = \frac{1}{\frac{H^3}{12EI_i} + \frac{H}{GA_i}} \quad (6)$$

In the equation: Δ_{mi} denotes the lateral displacement induced by the bending deformation of the i -th segmented column; Δ_{vi} represents the lateral displacement caused by the shear deformation of the i -th segmented column; D_i signifies the lateral stiffness of the i -th segmented column at a column height of H .

The cross-sectional area and moment of inertia of each unit column are identical, resulting in equivalent lateral displacement and lateral stiffness under unit force. Consequently, the lateral displacement of the i -th unit column can be derived as follows:

$$\Delta_1 = \frac{D_1}{(D_1 + D_2 + D_3 + D_4)} \left(\frac{FH^3}{12EI_1} + \frac{FH}{GA_1} \right) \quad (7)$$

Consequently, the formula for the lateral displacement stiffness under the integrated working effect of the four segmented columns is as follows:

$$D' = \frac{F}{\Delta_1} = \frac{4}{\frac{H^3}{12EI_1} + \frac{H}{GA_1}} = \frac{48EI_1GA_1}{12EI_1H + GA_1H^3} \quad (8)$$

By calculating the ratio between Equations (8) and (2) and simplifying, we obtain:

$$\frac{D'}{D} = \frac{48EI_1GA_1}{12EI_1H + GA_1H^3} \times \frac{GAH^3 + EIH}{12EIGA} = \frac{GAH^3 + EIH}{12EIH + 4GAH^3} < \frac{1}{4} \quad (9)$$

In Equation (9):

$$I_1 = \frac{I}{16} \quad (10)$$

$$A_1 = \frac{A}{4} \quad (11)$$

2.2.3. Lateral Stiffness of UHPC-NC Composite Columns Under Various Conditions

The average stiffness of UHPC columns varies under different conditions. Initially, the lateral stiffness of the entire column is calculated, with the selected design parameters presented in Table 1 [28]. The cross-sectional dimensions are a square with a length of 400 mm, and the net height of the column is half the floor height, set at 1400 mm. The UHPC column cross-sectional side lengths range from 140 mm to 180 mm, forming five groups of UHPC-NC composite columns. The data is then substituted into Formulas (7) and (8). For the overall ordinary concrete column ZT-1: $D = 2.27 \times 10^5$ N/mm, the lateral stiffness of the overall UHPC-NC composite column is $D = 3.33 \times 10^5$ N/mm, and the UHPC split column ZH-i. The calculation results are summarized in Table 1.

Table 1. The lateral stiffness of UHPC-NC composite columns in the “split column configuration”.

Specimen Number	UHPC Column Size (a × a) mm	Anti-Lateral Stiffness × 10 ⁵ N/mm
ZT-1	/	2.27
ZH-1	180 × 180	0.63
ZH-2	170 × 170	0.51
ZH-3	160 × 160	0.39
ZH-4	150 × 150	0.31
ZH-5	140 × 140	0.23

As shown in Table 1, the lateral drift stiffness of the integral UHPC-NC composite column is 3.33×10^5 N/mm, which is greater than that of the integral conventional concrete column (2.27×10^5 N/mm), indicating that the seismic performance of the UHPC-NC composite column in its integral form is not superior. When configured as a “split UHPC column,” the lateral drift stiffness is significantly reduced. For instance, the stiffness of ZH-5 in the split-column configuration is only one-tenth of that of the initial ZT-1 specimen. The lateral drift stiffness of each model in the split configuration varies substantially from that of the initial conventional concrete column, with ratios ranging between 3.6 and 10, resulting in higher flexibility that is more conducive to seismic resistance. Therefore, based on the theoretical analysis of lateral drift stiffness, it can be concluded that after the failure of the conventional concrete column, the UHPC-NC composite column exhibits reduced lateral drift stiffness. This enhances the flexibility of the split UHPC column, improves its horizontal deformation capacity, and ultimately strengthens the seismic performance of the UHPC-NC composite column. The design concept of this novel structural system is supported by lateral drift stiffness theory and aligns with practical engineering applications.

3. Finite Element Model of UHPC-NC Frame Structure

To analyze the dynamic response data curves of the UHPC-NC composite column frame structure under seismic action, this study established UHPC-NC composite column frame and RC column frame models using ABAQUS 2021, and conducted dynamic time-history analysis of seismic waves on the models.

3.1. The Establishment of the UHPC-NC Frame Structure Model

This paper presents the design of a five-story reinforced concrete frame structure, as illustrated in Figure 3. To highlight the seismic performance of short columns in the UHPC-NC composite column system, the first story height is set at 3 m. For modeling convenience, the column cross-sections are designed as 400 mm square, with both transverse and longitudinal beams sharing the same 400 mm square cross-section, and a slab thickness of 200 mm. The reinforced concrete frame structure is depicted in Figure 3a, while the UHPC-NC composite column frame structure is shown in Figure 3b. The UHPC column cross-sections are designed as 150 mm square, following the optimal cross-sectional combination design referenced in [28].

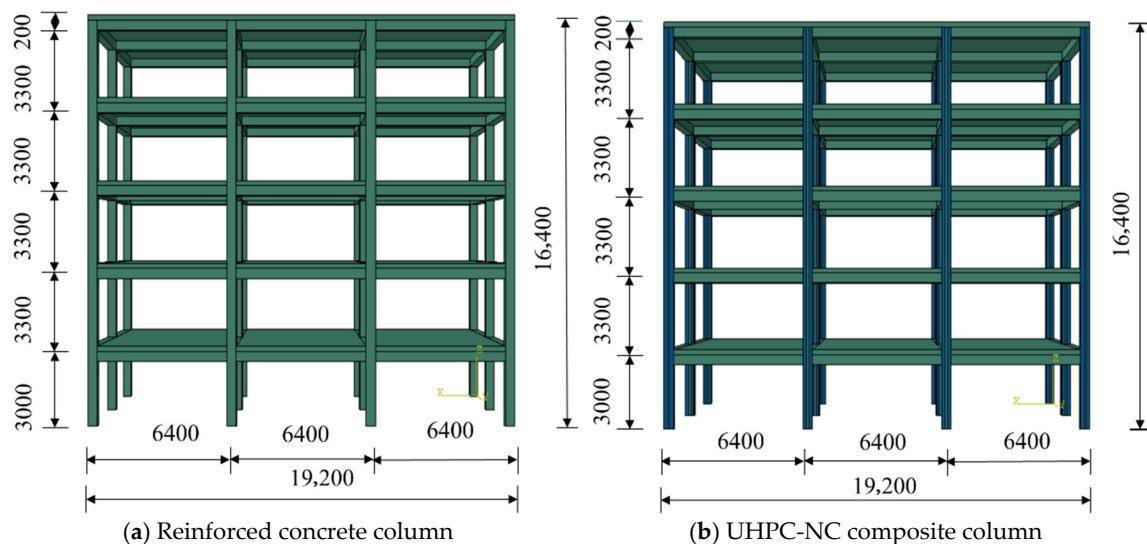


Figure 3. Schematic Diagram of Multi-tier Framework Architecture.

As illustrated in Figure 4, the reinforced concrete column structure corresponds to Figure 4a, where 16 $\Phi 16$ longitudinal bars are employed, and $\Phi 10@100$ stirrups are used for column reinforcement. The UHPC-NC composite column frame structure, depicted in Figure 4b, utilizes 16 $\Phi 16$ longitudinal bars and $\Phi 8@100$ stirrups, adhering to the principle of strong columns and weak beams in reinforcement design. The stirrup ratio in this configuration is essentially equivalent to that of reinforced concrete frame structure columns. Both frame structures share identical reinforcement details in other components, specifically: 4 $\Phi 18$ longitudinal bars for both longitudinal and transverse beams, $\Phi 10@150$ stirrups, 101 $\Phi 10@183.5$ longitudinal bars for the slab, and 51 $\Phi 10@247$ transverse bars for the floor slab.

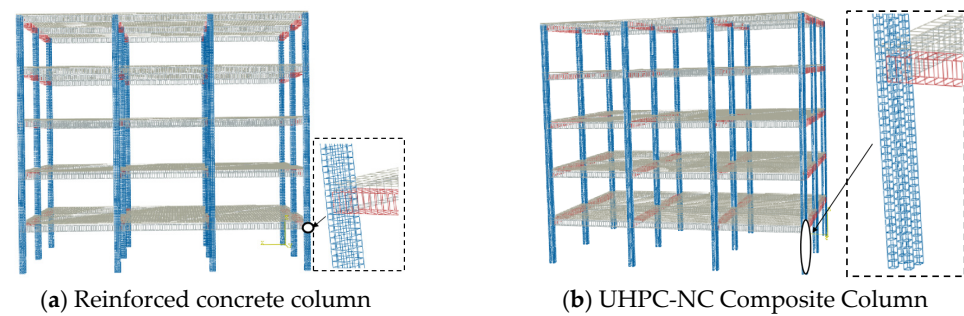


Figure 4. Reinforcement Schematic Diagram of Multi-story Frame Structure.

3.2. Materials and Their Constitutive Relationships

In this numerical simulation, the reinforcement steel is modeled using a bilinear constitutive relationship. For HRB400, the ultimate stress is set at 540 MPa, while for HRB335, it is 455 MPa, with an elastic modulus of 200 GPa and a Poisson's ratio of 0.3. The stress–strain relationship is illustrated in Figure 5. For concrete, the Concrete Damaged Plasticity (CDP) model is employed, with the constitutive relationship based on the concrete structure design code [31] (GB 50010-2010). C40 normal concrete is used, with an initial elastic modulus of 32.6 GPa, and its stress–strain curve is shown in Figure 6. For Ultra-High Performance Concrete (UHPC), the axial compressive stress–strain curve proposed by Yang Jian et al. [32] is adopted, and the UHPC-NC stress–strain constitutive relationship is established by referencing the axial compressive constitutive model of ordinary concrete in CEB-FIP [33]. In the finite element model of this section, the ultimate compressive strength of UHPC is taken as 139.46 MPa, corresponding to 3500 $\mu\epsilon$, with an initial elastic modulus of 42.6 GPa. For the tensile constitutive relationship, Zhang Zhe et al. [34] tested the stress–strain relationship of UHPC under axial tensile load, and the tensile constitutive model from this literature is utilized in this study.

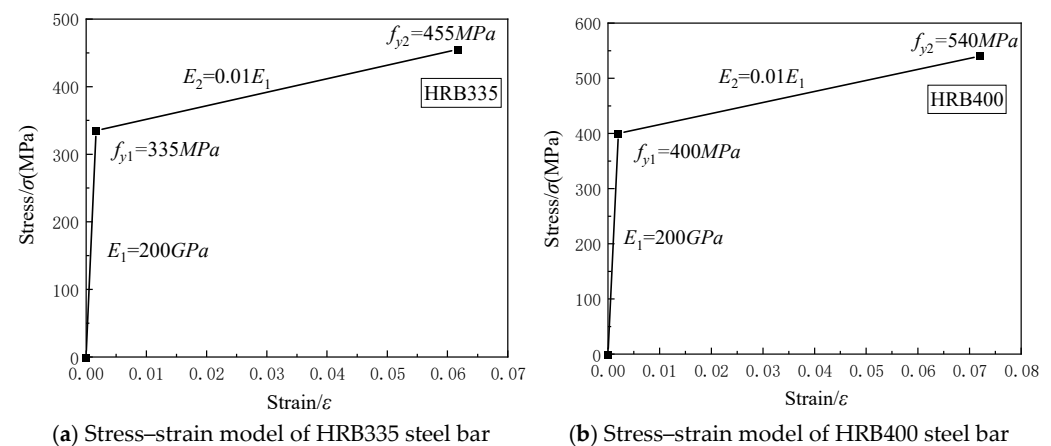


Figure 5. Steel bar constitutive relationship model.

During the modeling process, to ensure the UHPC-NC composite column functions as an integral structure, a monolithic column with a cross-sectional dimension of 400 mm × 400 mm was initially constructed. The partitioning feature in ABAQUS was then employed to dissect the monolithic column into five segments, comprising four corner elements and a central cruciform-shaped section. Material properties were subsequently assigned accordingly: the four corner elements were defined with the constitutive characteristics of ultra-high-performance concrete (UHPC), while the central cruciform section was assigned the constitutive properties of C40 normal concrete. This approach effectively addresses interface bonding considerations, enabling the UHPC-NC composite column to

resist horizontal seismic loading as a unified structural element. Consequently, it reduces the risk of computational interruptions in ABAQUS simulations and enhances the accuracy of the model predictions, thereby preventing distortions in the computational results.

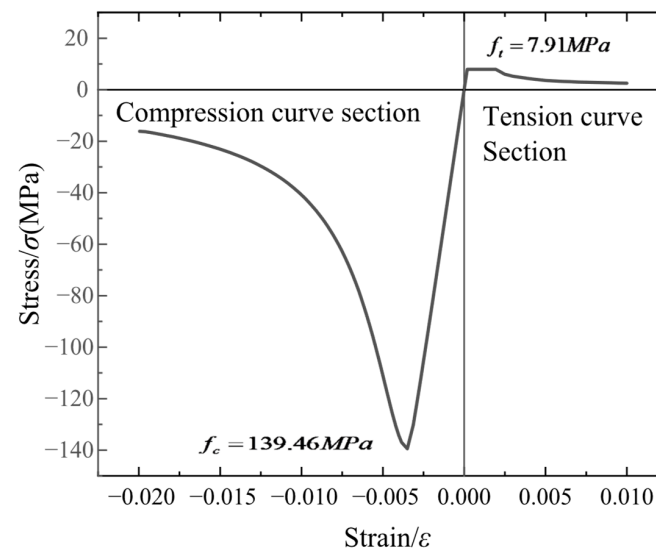


Figure 6. UHPC Stress–Strain Relationship Diagram.

To ensure computational accuracy in mesh generation, the authors adopted a dual-mesh strategy wherein ordinary concrete and UHPC were assigned distinct independent meshes. The mesh size was maintained within a side length range of 100 mm to 150 mm, thereby minimizing numerical distortions and reducing model errors.

3.3. Boundary Conditions and Loads

The model employs ABAQUS for finite element numerical simulation. Initially, modal analysis is conducted with the column base fixed, followed by linear perturbation analysis to compute the first 10 modes of the model. In this study, the Rayleigh damping coefficients are determined by calculating the proportional coefficients α and β using the frequencies of the first and second modes, as per the following formula:

$$\alpha = \frac{4\pi f_i f_j \xi}{(f_i + f_j)} \quad (12)$$

$$\beta = \frac{\xi}{\pi(f_i + f_j)} \quad (13)$$

In the equation: f_i represents the first-order natural frequency of the structure; f_j denotes the second-order natural frequency of the structure. ξ Material damping ratio.

Through modal analysis, the first-order frequency (f_1) and second-order frequency (f_2) are computed. Subsequently, the calculated proportional coefficients α and β are input into ABAQUS to define the material damping parameters, which are then utilized for seismic performance verification.

This study investigates the model subjected to loading along the X-axis, under the assumption that seismic wave effects in the Y-axis and Z-axis directions are negligible. Therefore, constraints are applied along the Y-axis and Z-axis directions, while rotational constraints are imposed in all other degrees of freedom.

To validate the accuracy of the ABAQUS computational results, an identical model was established using ANSYS software 2021. Consistent constitutive relationships for the materials and identical boundary conditions as those defined in ABAQUS were applied,

along with the same input parameters. Modal analysis was conducted on both the ordinary reinforced concrete column frame structure and the UHPC-NC composite column frame structure. Initially, the base of the frame columns was fully fixed, and the first ten modes of the model were calculated. The modal analysis results from ANSYS, including the first-order frequency (f_1) and the second-order frequency (f_2), were found to be consistent with the corresponding results obtained from ABAQUS, thereby mutually validating the accuracy of the ABAQUS computational outcomes.

During the nonlinear dynamic time-history loading phase, the loading analysis is divided into two steps: First, a gravity analysis is conducted on the structure, with fixed constraints applied at the base of the columns. Upon completion of the gravity analysis step, a longitudinal load is applied to the model, while constraints are imposed in other directions of the frame structure. The loading condition utilizes the El-Centro wave, as illustrated in Figure 7, with a duration of 20 s. The seismic acceleration loading is calculated for frequent earthquakes of magnitudes 7, 8, and 9, respectively.

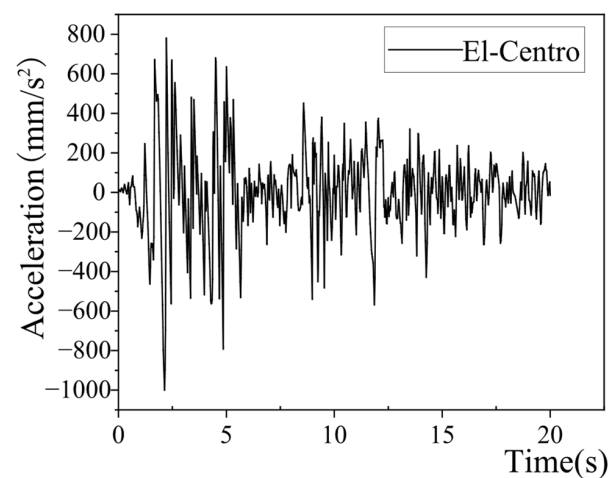


Figure 7. EL-Centro seismic wave.

To verify the structural response patterns under different seismic waves, computational simulations were conducted for the Hyogo-ken Nanbu wave (as illustrated in Figure 8) and the Kobe wave (as depicted in Figure 9) under the seismic acceleration loading condition of a Level 9 frequent earthquake. To capture the ultimate plastic deformation displacement of the frame structure, a 30 s simulation analysis was performed in ABAQUS, utilizing the inherent damping of the structure to achieve a static state. The extracted data more accurately reflects the actual plastic deformation characteristics of the structure.

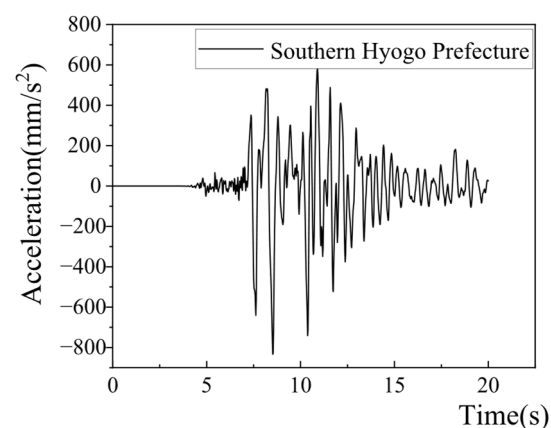


Figure 8. Seismic waves from the southern Hyogo Prefecture earthquake in Japan.

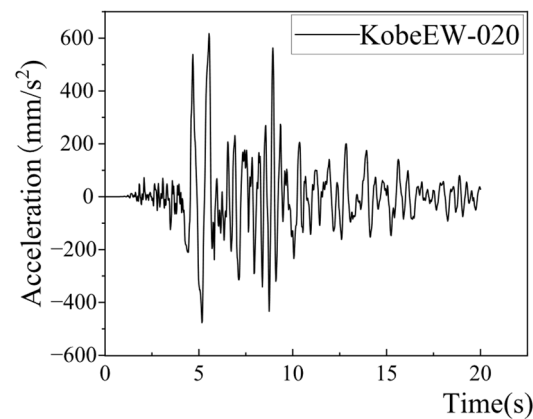


Figure 9. KobeEW-020 Seismic Wave.

4. Seismic Performance Analysis

4.1. Dynamic Damage Finite Element

Under seismic action, the damage condition of concrete directly reflects the structural damage state, thereby offering an intuitive indication of the seismic performance of the structure. This section focuses on analyzing the tensile damage of the structure, with the seismic performance evaluated based on the concrete tensile damage condition. In this study, the inelastic strain in the data structure input into the ABAQUS software 2021 corresponds to the damage factor. A tensile damage factor between 0.2 and 0.3 indicates moderate damage, while values exceeding 0.3 are also classified as moderate damage. It is generally accepted that when the tensile damage factor approaches 0.9, the tensile capacity of ordinary concrete is effectively reduced to zero. Given that concrete failure is predominantly governed by tensile damage, the tensile damage factor can be utilized to assess the damage distribution in frame structures. Under the loading conditions of frequent earthquakes corresponding to Intensity 7, 8, and 9 of the El-Centro wave, the structural damage diagrams were extracted and are presented in Figure 10, Figure 11, and Figure 12, respectively.

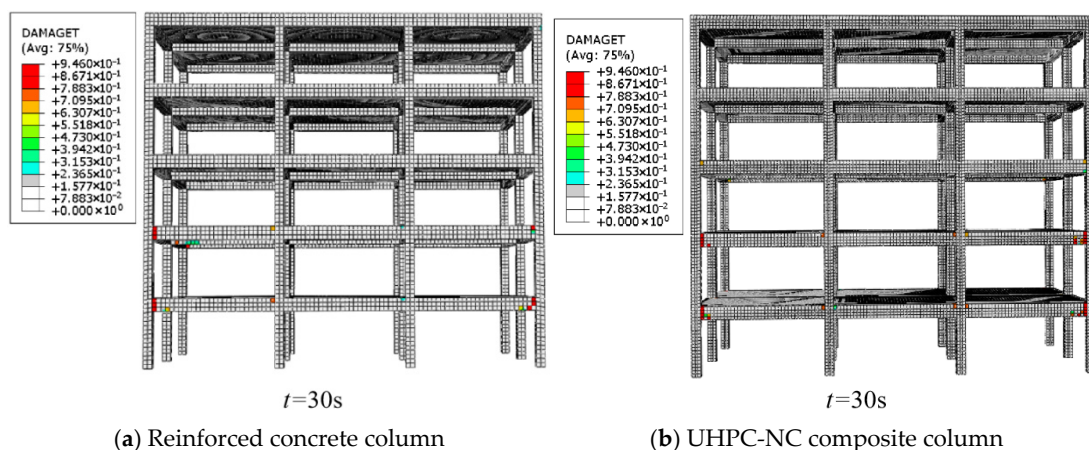


Figure 10. Structural damage diagram under M7 multi—occurrence earthquakes.

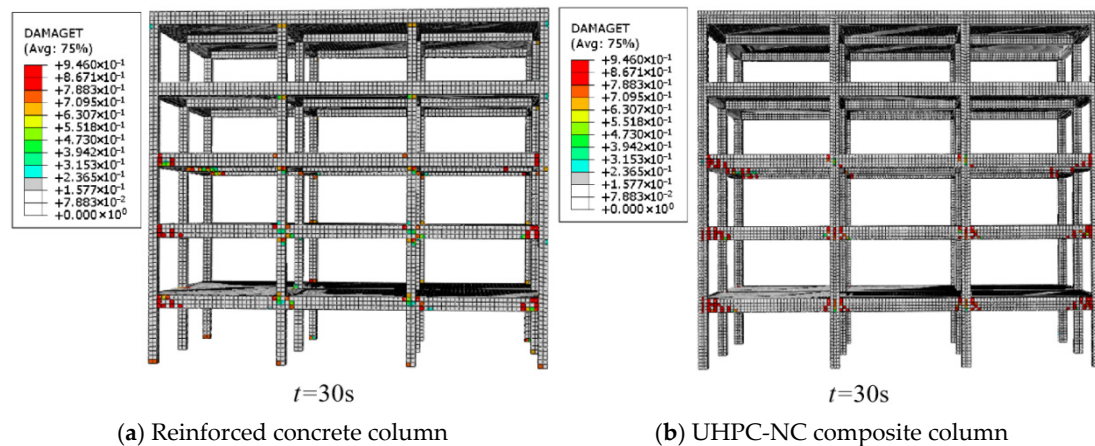


Figure 11. Structural damage diagram under M8 multi—occurrence earthquakes.

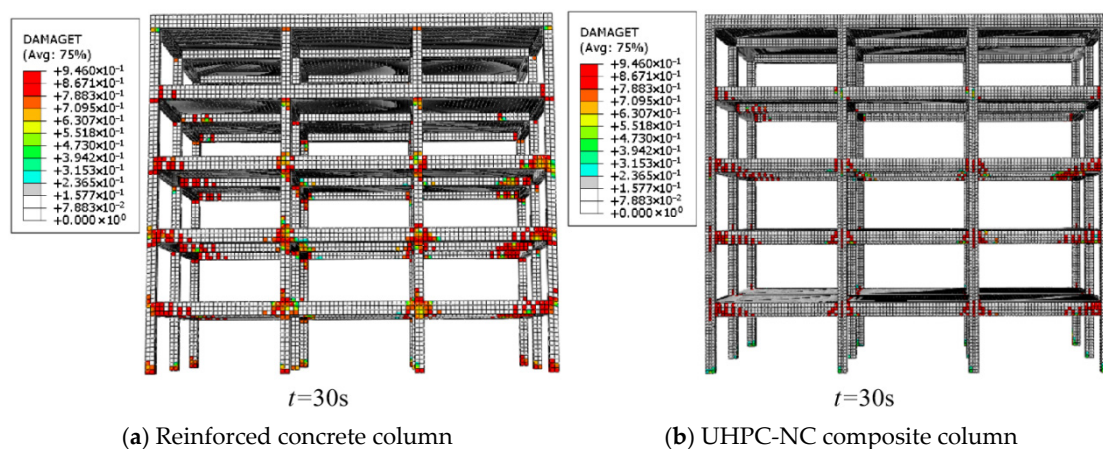


Figure 12. Structural damage diagram under multiple earthquakes of M9.

Figure 10 illustrates that under the loading condition of a frequent earthquake with intensity 7 (El-Centro wave), the tensile damage in ordinary concrete frame structures is concentrated at the beam–column joints of the first, second, and third stories. Although these structures have not reached complete failure, some beam–column joints exhibit tensile damage factors of $Dt = 0.946$, and partial joints demonstrate failure patterns, indicating susceptibility to damage at these locations. In contrast, the concrete frame structure with UHPC-NC composite columns experiences relatively minor tensile damage. Nonetheless, the tensile damage factor at certain beam–column joints also reaches $Dt = 0.946$, with some joints showing failure behavior and approaching a state of complete failure. Comparative analysis reveals that the tensile damage in the UHPC-NC composite column frame structure is essentially equivalent to that of the ordinary concrete frame structure, with beam–column joints remaining the primary zones of damage manifestation.

Figure 11 illustrates that under the seismic loading scenario corresponding to an 8-degree frequent earthquake, the ordinary concrete frame structure exhibits significant tensile damage. Specifically, tensile damage factors (Dt) of 0.946 are observed at certain beam–column joints, including those at the top story, where $Dt = 0.6307$. Additionally, the base of the columns shows pronounced tensile damage, with Dt reaching 0.7095, indicating severe damage. In contrast, the UHPC-NC composite column frame structure demonstrates substantially reduced tensile damage compared to the ordinary concrete frame. Tensile damage in the composite structure is confined to beam–column joints on the first, second, and third stories, as well as the bottom regions of longitudinal beams

near these joints. The tensile damage factor at some joints is $D_t = 0.946$, predominantly localized in areas composed of conventional concrete materials. The extent of damage is considerably smaller than that in the ordinary concrete frame, and no tensile damage is observed at the column bases.

Figure 12 demonstrates that under the loading condition of a magnitude-9 frequent earthquake, the ordinary reinforced concrete frame structure exhibits severe tensile damage, particularly at the beam–column joints and adjacent beam slabs. The base of the first-story columns suffers significant damage, with a tensile damage factor $D_t = 0.946$, indicating a high risk of structural collapse. Both the top and bottom of the intermediate-story columns are severely damaged, especially in the first and second stories. Longitudinal beams near the two rows of middle columns display crack damage perpendicular to the loading direction, with a tensile damage factor $D_t = 0.946$, reflecting extensive destruction. In contrast, the tensile damage in the UHPC-NC composite column frame structure is considerably less severe. Damage is mainly concentrated at the beam–column joints, specifically in the column top joint areas from the first to the third stories, with no significant tensile damage observed on the UHPC columns. Although noticeable tensile damage occurs at the beam nodes near the columns, its extent is substantially lower than that in the ordinary concrete frame structure. Tensile damage is also present at the column bases, with a damage factor $D_t = 0.3942$, indicating no risk of collapse. This satisfies the design objective of preventing collapse under major seismic events.

Under the loading condition of a Level 9 frequent earthquake, the tensile damage diagrams of the structures subjected to Seismic waves from the southern Hyogo Prefecture earthquake in Japan and KobeEW-020 Seismic Wave are illustrated in Figures 13 and 14, respectively.

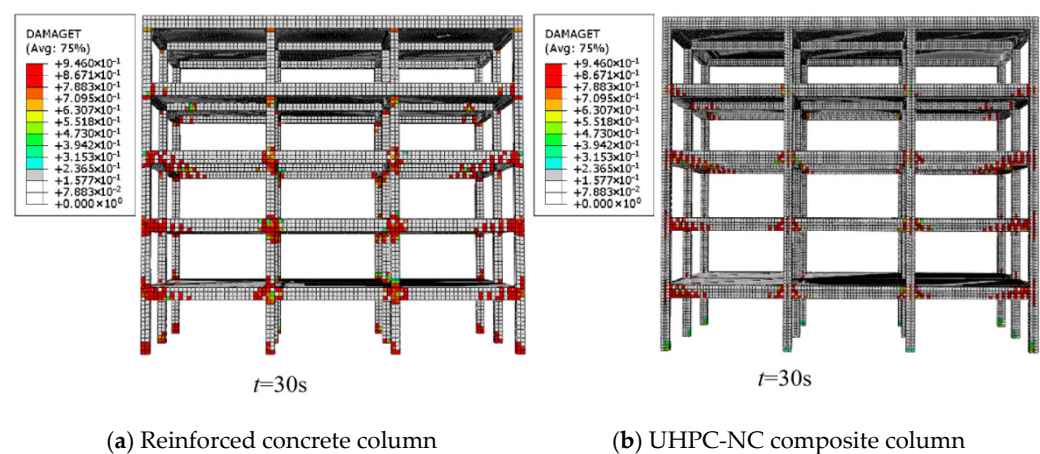


Figure 13. Tensile damage diagram of wave loading the southern Hyogo Prefecture earthquake in Japan.

Figures 13 and 14 demonstrate that the tensile damage of the ordinary concrete frame column structure is notably more pronounced. In the UHPC-NC composite column frame structure, tensile damage occurs at the base of the columns; however, it does not lead to the degradation of the mechanical performance of the UHPC material. In contrast, severe damage is observed at the base of the ordinary concrete frame columns, with a tensile damage factor $D_t = 0.946$, indicating a risk of structural collapse under such conditions. Furthermore, the beam–column joints at the top of the first and second floors in the ordinary concrete frame column structure exhibit significant tensile damage, with a tensile damage factor $D_t = 0.946$, reflecting the structure’s inferior seismic performance. The tensile damage in the UHPC-NC composite column frame structure is comparatively less severe, although localized areas of ordinary concrete in some beam–column joints sustain notable damage. Tensile damage is also present at the base of the columns, with a tensile damage factor

$Dt = 0.3942$, classified as severe damage; nevertheless, there is no risk of structural collapse. By comparison with Figure 12, it is apparent that under the action of the three seismic waves at the frequent earthquake intensity level of magnitude 9, the tensile damage patterns are consistent. The UHPC-NC composite column frame structure exhibits superior tensile resistance, thereby contributing favorably to the seismic performance of the structure.

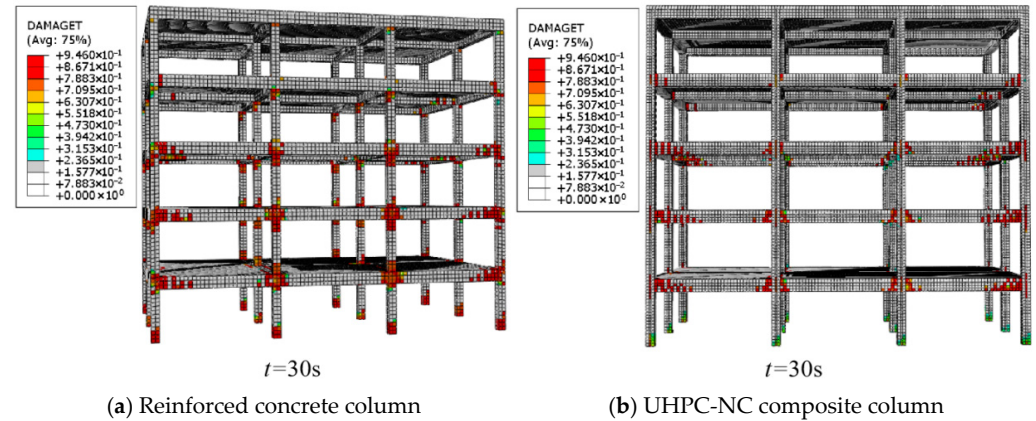


Figure 14. KobeEW-020 tensile damage diagram under wave loading.

4.2. Displacement Response Curve

For the purpose of quantitative comparison, this study presents the peak displacement responses of the seismic waves El-Centro Wave, Southern Wave, Hyogo Prefecture, Japan, and KobeEW-020 Wave. As shown in Table 2, which lists the maximum displacements of various seismic waves, the displacement of the UHPC-NC composite column frame (denoted as Δ_1) and the displacement of the reinforced concrete frame (denoted as Δ_2) are considered. The corresponding displacement reduction ratio is calculated as follows:

$$\lambda = \left| \frac{\Delta_1 - \Delta_2}{\Delta_2} \right| \times 100\% \quad (14)$$

Table 2. Peak Displacement Table (Unit: mm).

Seismic Wave	Number of Layers	First Floor	Second Floor	Three Floor	Fourth Floor	Fifth Floor
El-Centro Wave	UHPC-NC composite column frame	6.333	−16.663	−25.633	−30.719	−32.635
	Reinforced concrete frame	9.161	17.934	−27.347	−32.902	−34.848
	Displacement Reduction Ratio λ	30.87%	7.09%	6.27%	6.63%	6.35%
Southern Wave, Hyogo Prefecture, Japan	UHPC-NC composite column frame	8.917	18.241	24.101	−29.641	−31.903
	Reinforced concrete frame	−11.041	21.802	28.231	−31.981	−33.702
	Displacement Reduction Ratio λ	18.61%	16.33%	14.63%	7.32%	5.34%
KobeEW-020 Wave	UHPC-NC composite column frame	11.377	25.198	35.308	40.627	42.472
	Reinforced concrete frame	−15.800	−34.448	−46.964	−52.828	55.355
	Displacement Reduction Ratio λ	28.00%	26.85%	24.82%	23.10%	23.27%

The displacement amplitude of seismic waves increases with ascending floor levels. For the UHPC-NC composite column frame, the maximum reduction rate of displacement Δ_1 relative to displacement Δ_2 of the reinforced concrete frame at the first story ranges between 18.61% and 30.87%, indicating a substantial improvement in structural seismic performance. Under the Southern Wave from Hyogo Prefecture, Japan, the peak displacement is reduced by 5.34% to 18.61%, while a more pronounced reduction of 23.27% to 28.00% is observed under the KobeEW-020 Wave, demonstrating the superior effectiveness of the UHPC-NC composite column frame in mitigating displacement under KobeEW-020 Wave excitation.

This section takes the structural displacement response curves under the action of a 9-level frequent earthquake as the analysis object, as shown in Figure 15. In the figure, ZH-*i* represents the *i*-th floor of the UHPC-NC composite column concrete frame structure, and ZT-*j* represents the *j*-th floor of the ordinary concrete frame structure.

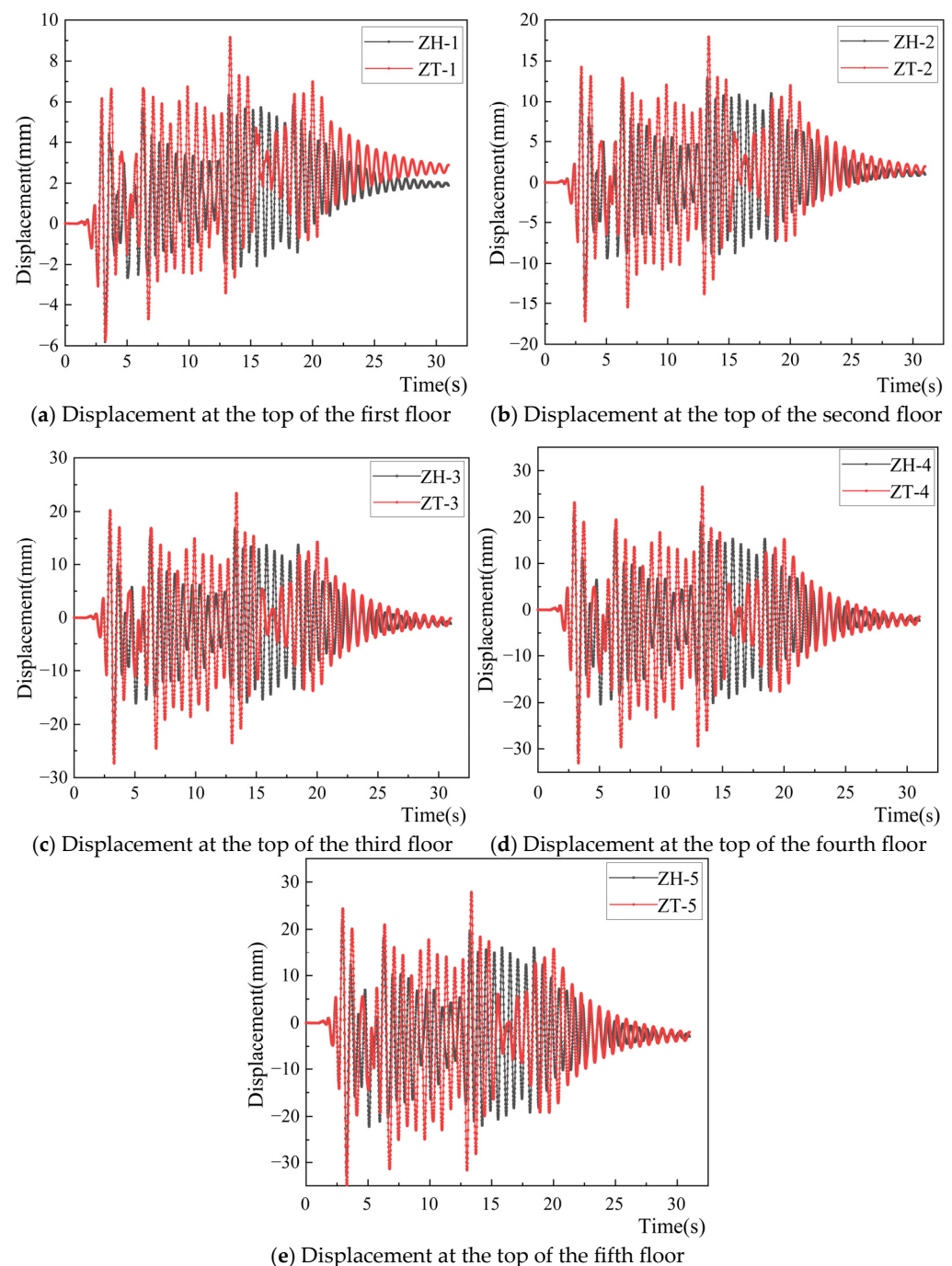


Figure 15. Displacement Response Curve of Structure under Level 9 Frequent Earthquake Action.

Analysis of Figure 15 reveals that the plastic displacements of the first and second stories of the UHPC-NC composite column frame structure in the loading direction are significantly smaller than those of the ordinary concrete frame structure. The discrepancy is particularly pronounced in the first story, where the plastic displacement is reduced by 30.87%, indicating that the UHPC-NC composite column frame structure exhibits superior seismic resistance under strong earthquake conditions. In contrast, the differences in plastic displacements along the loading direction for the third, fourth, and fifth stories of

the composite column frame structure are comparatively minor, with peak displacement reduction rates ranging from 6.35% to 7.09%.

The comparative analysis of peak inter-story drifts reveals that the composite column frame structure exhibits significantly smaller peak displacements, with a relative reduction ratio ranging from 6.35% to 30.87%, due to its enhanced lateral stiffness compared to conventional reinforced concrete frame structures. This observation substantiates the viability of applying UHPC-NC composite columns to seismic design methodologies for their superior seismic performance. A comprehensive evaluation of Figure 15 further demonstrates that the composite column frame structure possesses greater damping capacity, which aligns with and corroborates the computationally derived damping values.

As illustrated in Figure 16, the displacement response curves under the seismic action of the Hyogo-ken Nanbu Earthquake are presented. Analysis of Figure 16 reveals that the displacement of the UHPC-NC composite column frame structure is relatively minor, with a displacement reduction rate of 18.61%. A comprehensive comparison of the final displacement response curves from the second to fifth floors indicates slightly smaller displacements in the UHPC-NC composite column frame structure, with displacement reduction rates ranging from 5.34% to 16.33%. At peak displacement, all floors exhibit greater displacement values in the ordinary concrete frame structure, demonstrating the superior tensile resistance and smaller plastic displacement of the UHPC-NC composite column frame structure.

Figure 17 illustrates the displacement response curves under the KobeEW-020 seismic excitation. As shown in Figure 17, under the action of the KobeEW-020 wave at $t = 30$ s, the ultimate displacement response of each story is lower in the UHPC-NC composite column frame structure, indicating reduced plastic deformation of the overall structure. In terms of peak displacement, the UHPC-NC composite column frame structure exhibits a smaller peak displacement, with a reduction rate ranging from 23.27% to 28.00%. This result reflects the greater plastic deformation and inferior seismic performance of the conventional concrete structure. In summary, under the three seismic loading scenarios, the structural displacements exhibit a consistent trend, demonstrating the superior seismic performance of the UHPC-NC composite column frame structure.

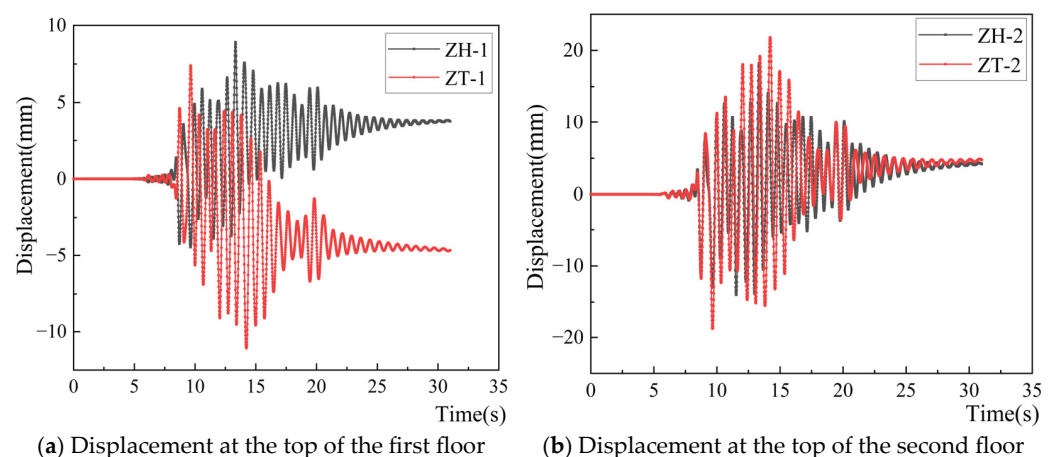


Figure 16. Cont.

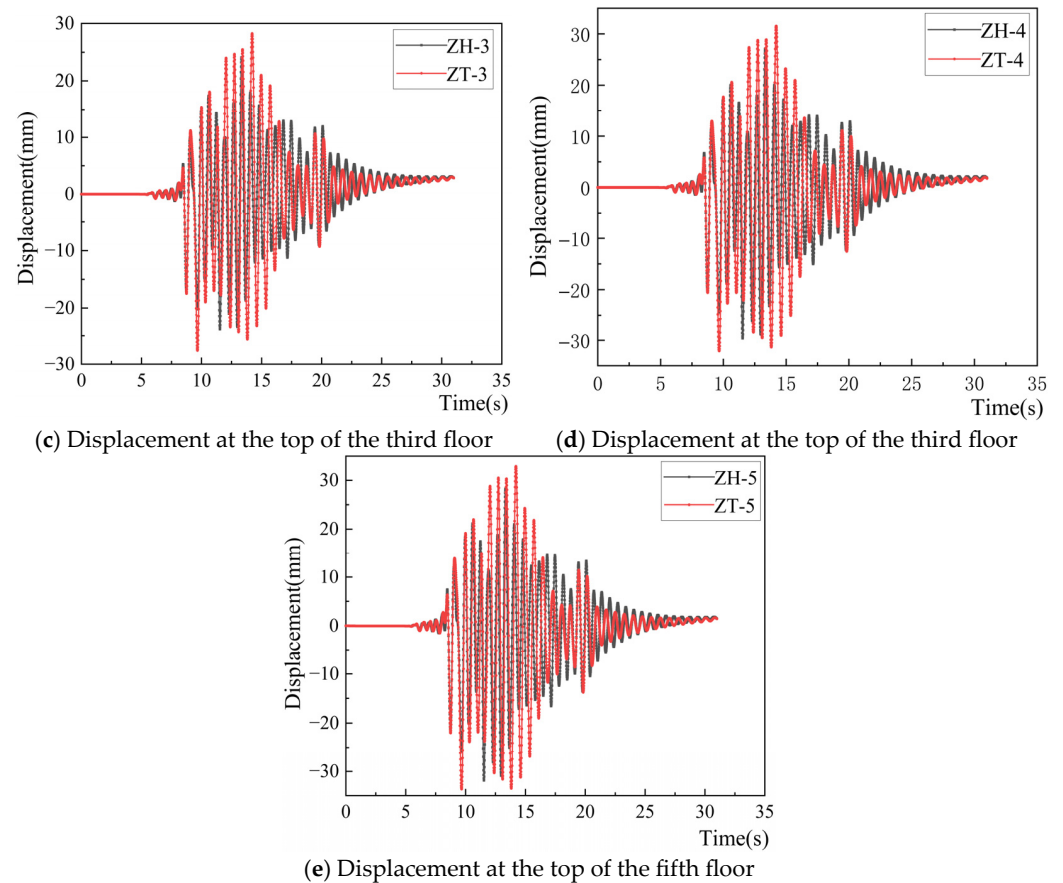


Figure 16. Displacement Response Curve under Wave Action in Southern Hyogo Prefecture.

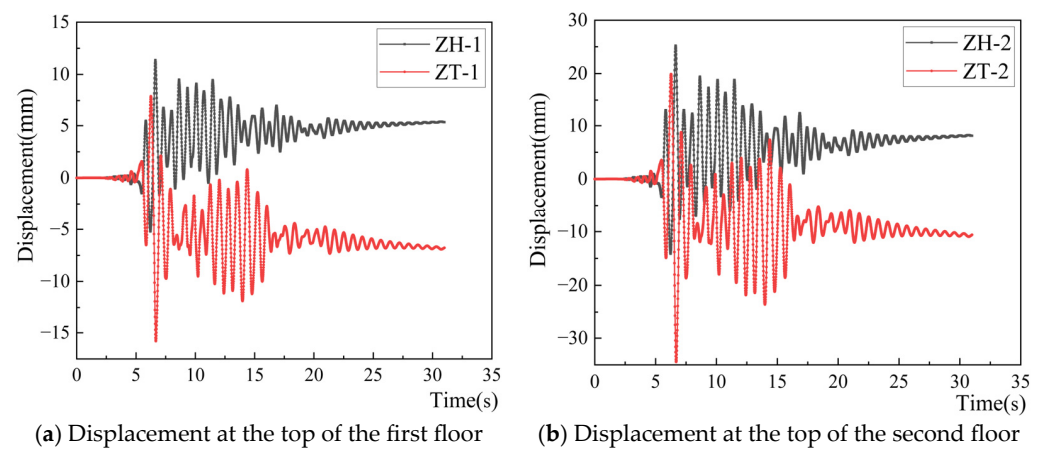


Figure 17. Cont.

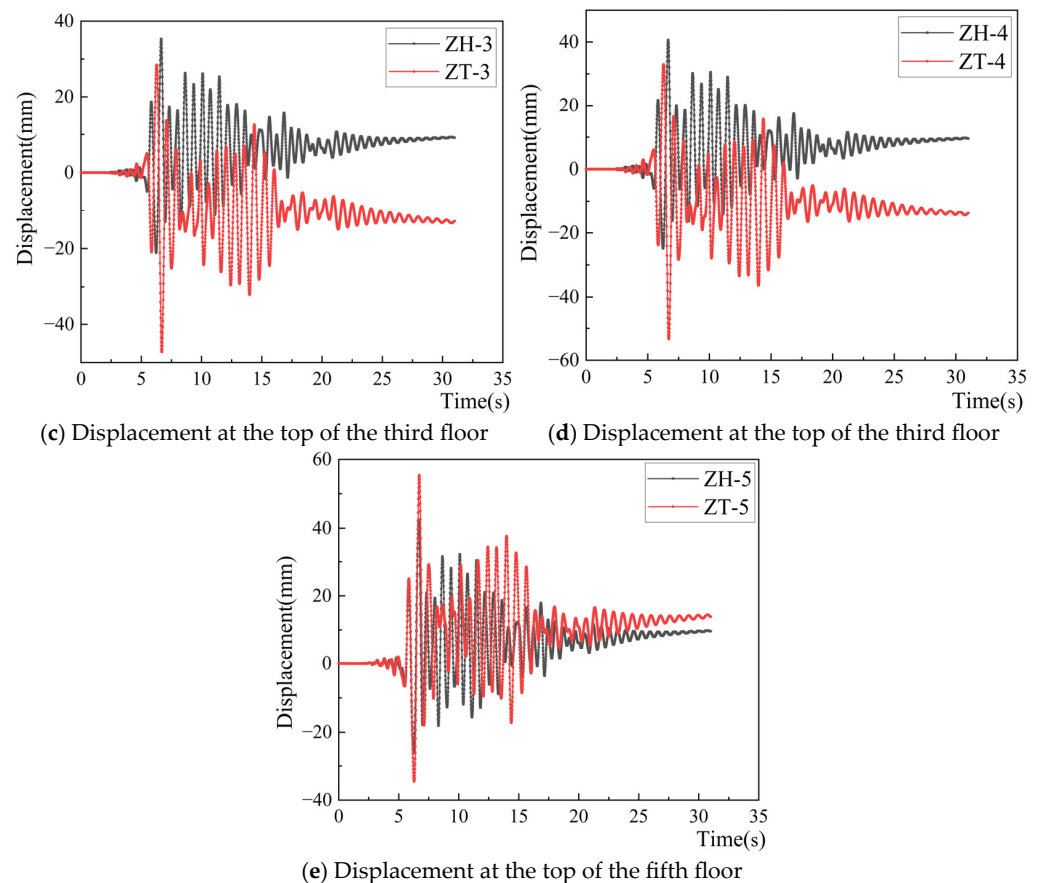


Figure 17. Displacement Response Curve under KobeEW-020 Wave Action.

4.3. Interlayer Displacement Angle

To visually represent the inter-story displacement data, Table 3 is provided as follows: According to the seismic design code [32], the inter-story displacement plastic angle of 1/550 is adopted as the evaluation criterion.

Table 3. Inter-Story Drift Ratio Data.

	Number of Layers	First Floor $\times 10^{-3}$	Second Floor $\times 10^{-3}$	Three Floor $\times 10^{-3}$	Fourth Floor $\times 10^{-3}$	Fifth Floor $\times 10^{-3}$
Level 9	UHPC-NC composite column frame	2.111	−3.338	−2.845	−1.699	−0.665
	Reinforced concrete frame	3.054	−3.524	−3.120	−1.816	−0.684
Level 8	UHPC-NC composite column frame	−1.180	−1.774	−1.379	−0.784	−0.372
	Reinforced concrete frame	−1.333	−1.989	−1.633	−0.916	−0.462
Level 7	UHPC-NC composite column frame	0.768	−0.838	−0.745	0.513	−0.270
	Reinforced concrete frame	−0.780	−0.972	−0.797	−0.551	−0.299

As indicated in Table 3, under seismic action of magnitude 7, the plastic hinge rotations of both frame structural models at each story level did not reach the specified limit values. Under seismic action of magnitude 8, the conventional frame-column structure reached the plastic hinge evaluation threshold at the second story; however, the UHPC-NC composite column frame structure did not, and the inter-story drift angle at the second story was approximately 10% smaller by comparison. This indicates that the UHPC-NC composite column frame structure exhibits superior seismic performance under El-Centro wave excitation at magnitude 8. Under seismic action of magnitude 9, neither the fourth nor the fifth story of either structure reached the plastic hinge limit, but it can be observed that the plastic hinge rotations of the UHPC-NC composite column frame were smaller.

Therefore, the UHPC-NC composite column frame structure is relatively safer with less plastic damage. For both structural types, the inter-story drift plastic angles exceeded the design code limits. The plastic drift angles of the UHPC-NC composite column frame from the first to the fourth story were 5% to 31% smaller than those of the conventional counterpart. In both frame types, the inter-story drift plastic angles remained below the quasi-static simulation's ultimate relative deformation value of 0.0114 [28].

Under the action of a Level 9 frequently occurring earthquake, the inter-story drift angles of different seismic waves are presented in Table 4. As indicated in Table 4, the KobeEW-020 wave loading resulted in the maximum inter-story drift angle for this group of frame structures. Across all three seismic wave loadings, the UHPC-NC composite column frame structures consistently displayed smaller inter-story drift angles, indicating superior seismic performance compared to traditional reinforced concrete frame structures under various seismic conditions. Under the 9-degree seismic action, neither the fourth nor the fifth story of the UHPC-NC composite column frame structure exceeds the plastic inter-story drift angle specified in the seismic design code. In contrast, the first four stories of the ordinary concrete frame structure surpass this limit. The plastic drift angles of the UHPC-NC composite column frame structure from the first to the fourth story are 5% to 31% smaller. The inter-story plastic drift angles of both structural systems remain below the quasi-static numerical simulation's ultimate relative deformation value of 0.0114. Therefore, the UHPC-NC composite column frame structure is more suitable for seismic-resistant design.

Table 4. Interlayer displacement angles under different seismic waves.

Seismic Wave	Number of layers	First Floor $\times 10^{-3}$	Second Floor $\times 10^{-3}$	Three Floor $\times 10^{-3}$	Fourth Floor $\times 10^{-3}$	Fifth Floor $\times 10^{-3}$
El-Centro Wave	UHPC-NC composite column frame	2.111	3.338	2.845	1.699	0.665
	Reinforced concrete frame	3.054	3.524	3.121	1.818	0.684
Southern Wave, Hyogo Prefecture, Japan	UHPC-NC composite column frame	2.973	3.063	3.006	1.751	0.687
	Reinforced concrete frame	3.355	3.299	3.058	1.861	0.706
KobeEW-020 Wave	UHPC-NC composite column frame	3.792	4.208	3.131	1.678	0.577
	Reinforced concrete frame	5.266	5.713	4.053	1.969	0.624

To elucidate the inter-story relative displacement values more clearly, the authors have presented the maximum displacement values for each seismic record and explicitly quantified the percentage differences between UHPC-NC and RC structures. As shown in Table 5, which displays the inter-story displacement values under three seismic waves, the ultimate inter-story displacement of this study is 37.62 mm, and the displacement values at each story level are significantly lower than this threshold. Under the El-Centro wave, the inter-story displacement values of the UHPC-NC composite column frame are reduced by 3.10% to 30.87% compared to those of the reinforced concrete frame. In contrast, the reductions observed under the Kobe EW-020 wave are generally more substantial, ranging from 7.77% to 26.31%.

Table 5. Inter-story Displacement Values under Various Seismic Wave Excitations.

Seismic Wave	Number of Layers	First Floor	Second Floor	Three Floor	Fourth Floor	Fifth Floor
El-Centro Wave	UHPC-NC composite column frame	6.33	17.35	9.39	5.61	2.19
	Reinforced concrete frame	9.16	20.79	10.30	6.00	2.26
	Displacement Reduction Ratio λ	30.87%	16.55%	8.83%	6.50%	3.10%
Southern Wave, Hyogo Prefecture, Japan	UHPC-NC composite column frame	8.92	10.11	9.92	5.78	2.27
	Reinforced concrete frame	10.07	10.89	10.09	6.14	2.33
	Displacement Reduction Ratio λ	11.42%	7.16%	1.68%	5.86%	2.58%
KobeEW-020 Wave	UHPC-NC composite column frame	11.38	13.89	10.33	5.54	1.90
	Reinforced concrete frame	15.80	18.85	13.38	6.50	2.06
	Displacement Reduction Ratio λ	18.61%	26.31%	22.80%	14.77%	7.77%

To better illustrate the inter-story drift ratios under seismic conditions, this study presents the plastic displacement values for each floor under the action of three seismic waves, as depicted in Figure 18. It is visually evident that the maximum inter-story displacement occurs at the second story across all three seismic scenarios. The conventional reinforced concrete frame exhibits significantly large inter-story displacements, whereas the UHPC-NC composite column frame demonstrates comparatively smaller displacements. Both displacement values remain below the predefined threshold for ultimate displacement.

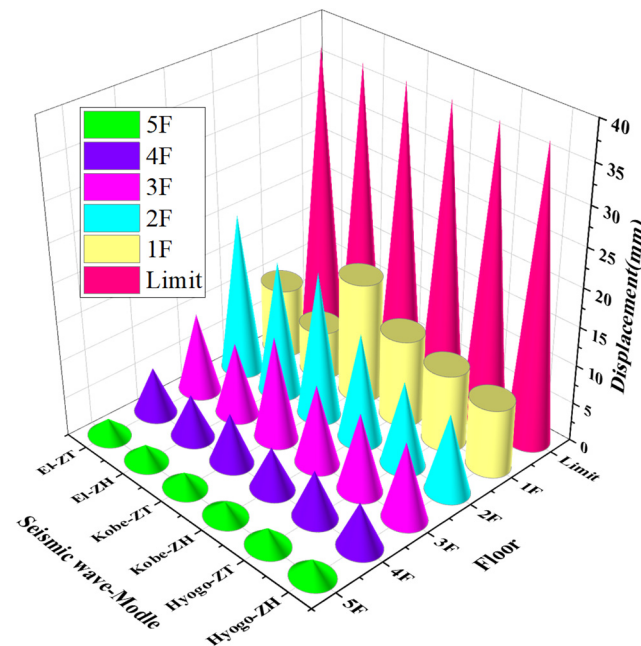


Figure 18. Inter-Story Drift Values at Each Floor Level Under Seismic Action of Magnitude 9.

4.4. Acceleration Response Curve

For clarity in presenting the peak acceleration responses of the three seismic waves across different floor levels, the author presents Table 6. The peak input acceleration for the El-Centro Wave is -1000 mm/s^2 , for the Southern Wave, Hyogo Prefecture, Japan, it is -833.66 mm/s^2 , and for the KobeEW-020 Wave it is 617.14 mm/s^2 . Based on the data in Table 5, it can be observed that the KobeEW-020 Wave exhibits the largest amplification factor. The amplification factor for the UHPC-NC composite column frame ranges from 2.58 to 3.91, while that for the El-Centro Wave ranges from 1.70 to 2.66, and for the Southern Wave, Hyogo Prefecture, Japan, it ranges from 1.80 to 2.98.

Table 6. Peak Accelerations Under Various Seismic Wave Excitations (Unit: mm/s^2).

Seismic Wave	Number of Layers	First Floor	Second Floor	Three Floor	Fourth Floor	Fifth Floor
El-Centro Wave	UHPC-NC composite column frame	1702.79	2288.62	−2410.81	−2343.03	2668.90
	Reinforced concrete frame	−1282.02	1683.42	−1997.30	−2284.25	−2615.76
	Ratio of Acceleration Values	1.33	1.36	1.21	1.03	1.03
Southern Wave, Hyogo Prefecture, Japan	UHPC-NC composite column frame	−1500.02	−1623.33	2118.03	−2408.15	2481.42
	Reinforced concrete frame	−1349.64	−1677.68	1857.58	2133.83	2381.19
	Ratio of Acceleration Values	1.11	0.97	1.14	1.13	1.04
KobeEW-020 Wave	UHPC-NC composite column frame	1592.37	2058.74	2340.55	2405.02	2414.90
	Reinforced concrete frame	1464.56	2148.49	2260.71	2119.43	2338.44
	Ratio of Acceleration Values	1.09	0.96	1.04	1.13	1.03

As illustrated in Figure 19, the acceleration response curves under the action of a Level 9 El-Centro seismic wave demonstrate that the peak accelerations across all stories of the UHPC-NC composite column frame structure are greater than those of the con-

ventional reinforced concrete frame structure, ranging from 1.03 to 1.36 times higher. In comparison, the acceleration response of the conventional frame structure is generally higher throughout the entire loading duration, indicating that the seismic response of the conventional frame column structure is more severe, which is detrimental to seismic resistance. In contrast, the acceleration attenuation in the UHPC-NC composite column frame structure occurs more rapidly, facilitating faster energy dissipation and thereby enhancing its seismic performance.

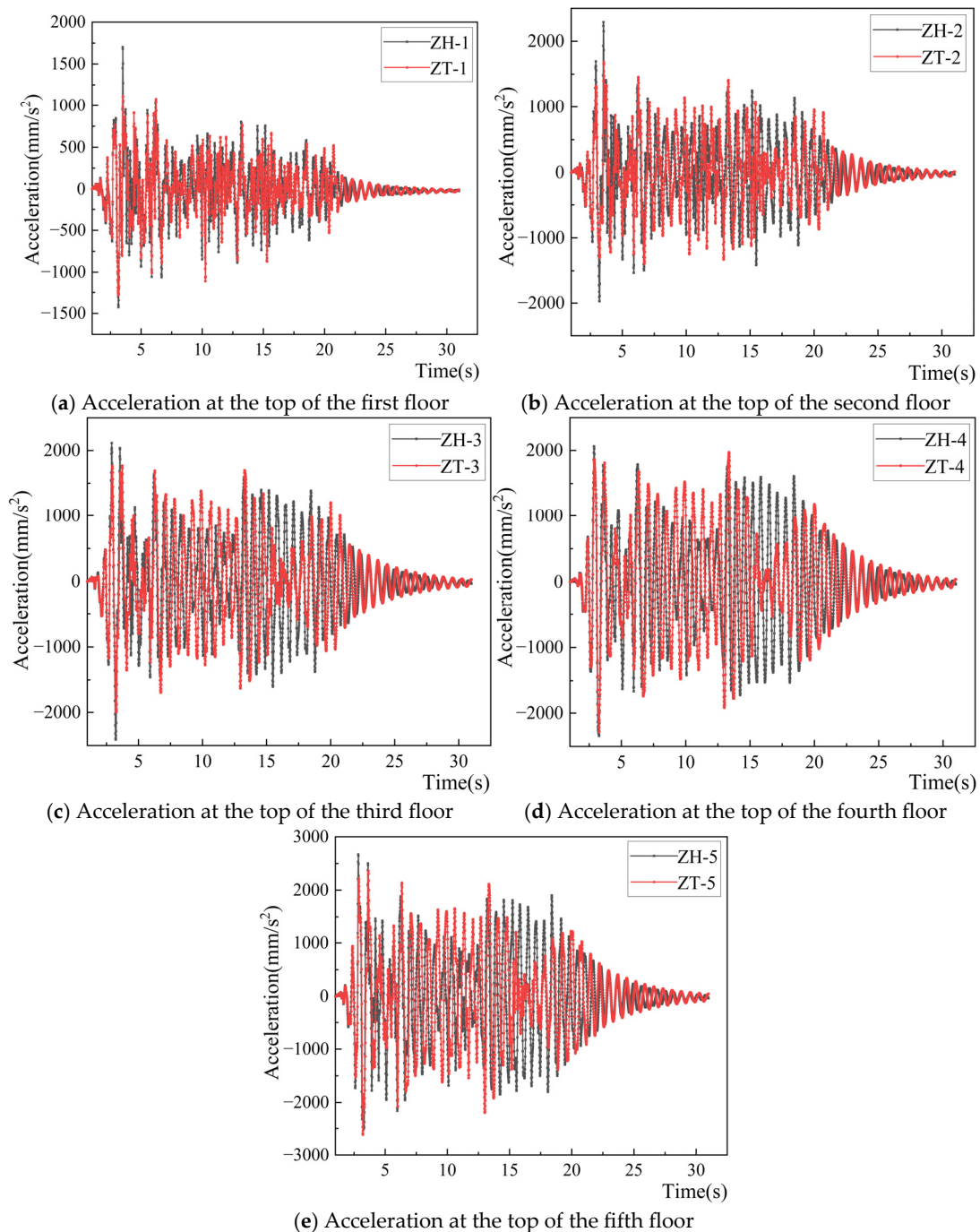


Figure 19. Acceleration response curve of M 9 earthquake.

Figure 20 illustrates the acceleration response curves under wave loading conditions in the southern part of Hyogo Prefecture, Japan. It can be observed from Figure 20 that, with the exception of the second story, the peak acceleration of the UHPC-NC composite column

frame structure is generally greater, ranging from 1.04 to 1.14 times that of the comparison model. Overall, the UHPC-NC composite column frame structure exhibits a more rapid acceleration response. After unloading, the structure also demonstrates higher acceleration values, indicating that the damping ratio of UHPC material is superior to that of conventional concrete. This enhanced damping facilitates faster energy dissipation and enables the structure to cease motion more promptly following the cessation of seismic activity.

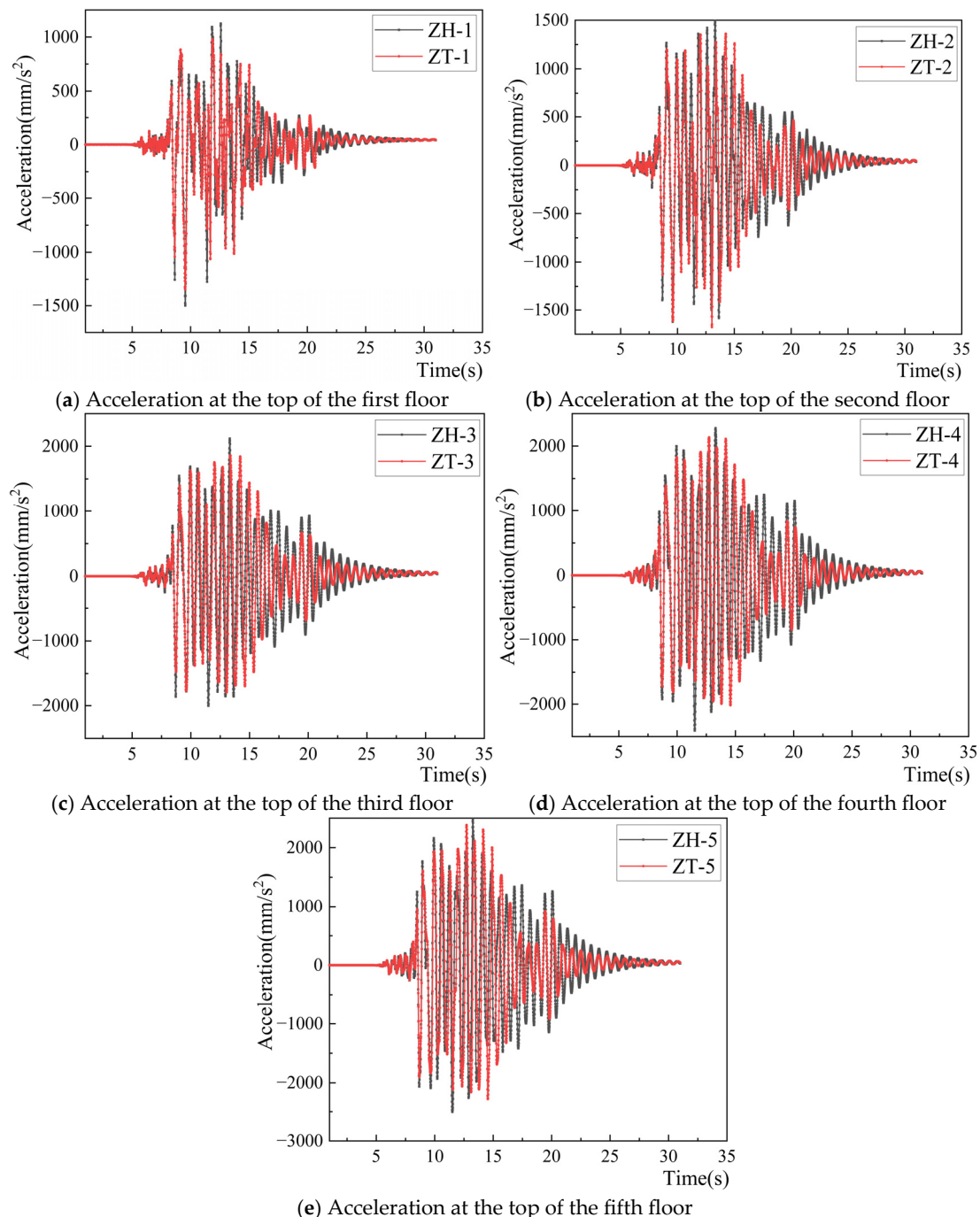


Figure 20. Acceleration response curve of wave in southern Hyogo Prefecture.

As illustrated in Figure 21, the acceleration response curves of the UHPC-NC composite column frame structure under the KobeEW-020 wave loading condition demonstrate that, with the exception of the second story, the peak acceleration is greater than that of the ordinary concrete frame structure, ranging from 1.03 to 1.13 times higher. Similarly, the

UHPC-NC composite column frame structure exhibits a more rapid acceleration response. After unloading, it shows a higher residual acceleration, indicating that the damping ratio of the UHPC-NC composite column frame structure is larger than that of the conventional concrete frame structure.

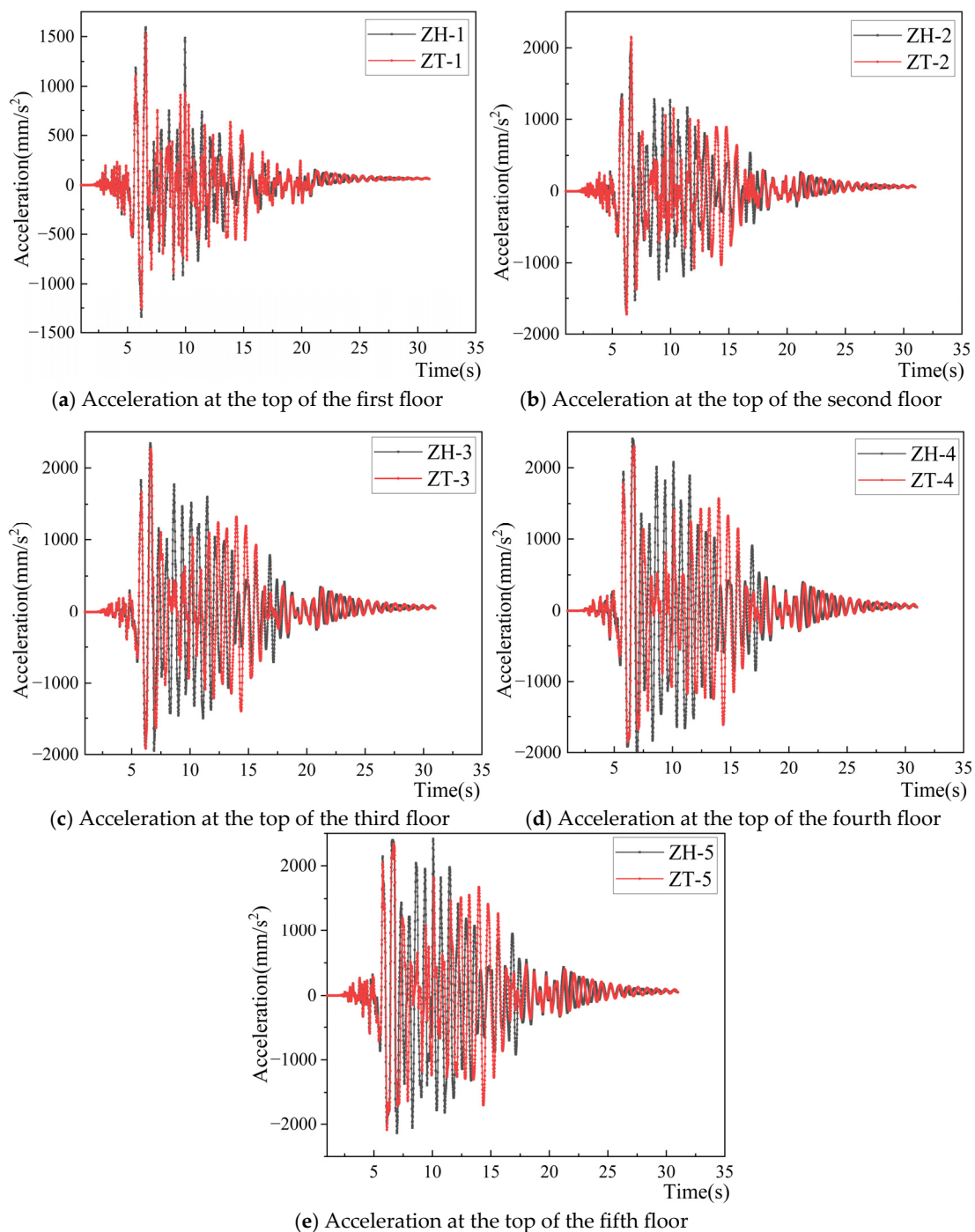


Figure 21. KobeEW-020 wave acceleration response curve.

Based on the comparative analysis under seismic excitations from the southern Hyogo wave, KobeEW-020 wave, and El-Centro wave, the acceleration response curves of the UHPC-NC composite column frame structure consistently demonstrate the following pattern: the faster the energy dissipation of the UHPC-NC composite column frame, the more favorable it is for seismic resistance, indicating superior design performance. Specifically, the acceleration response of the UHPC-NC composite column frame is greater

than that of the conventional concrete frame structure, while the damping ratio of the former is also higher. The characteristics of the acceleration response curve align with the theoretical verification of the stiffness-drift relationship presented in this study.

5. Discussion

This study investigates the seismic performance of UHPC-NC composite column frame structures compared with conventional concrete frame structures. UHPC-NC composite column frames are recommended for use in high-seismic-intensity zones, demonstrating significantly enhanced seismic resistance relative to ordinary concrete frames. The lateral stiffness of the split-column configuration decreases substantially, measuring only 1/4 to 1/10 of the initial stiffness of conventional concrete columns, resulting in a 4 to 10-fold increase in flexibility. The peak displacement reduction rate ranges from 5.34% to 30.87%, and the acceleration response factor varies between 0.96 and 1.36. The inter-story drift reduction ratio is between 1.68% and 30.87%. Under seismic intensities of 7 and 8, tensile damage remains minor, while under intensity 9, severe damage occurs at the base of the first-story columns without reaching failure. In contrast, conventional concrete frames exhibit a risk of collapse under similar conditions. Overall, UHPC-NC composite column frames exhibit superior seismic performance. However, to promote the application of UHPC-NC composite columns, efforts should focus on prefabricated and modular components. Industrialized production can enhance efficiency and reduce construction costs. Therefore, future research should prioritize the seismic behavior of prefabricated UHPC-NC composite column frame systems. This study also lacks a vulnerability analysis of UHPC-NC composite column frames and requires verification under additional seismic wave loading conditions. Further investigation into the failure mechanisms of such structures is also warranted.

6. Conclusions

This study employs the ABAQUS finite element software to conduct quasi-dynamic numerical simulation analyses on both UHPC-NC composite column frame structures and reinforced frame structures. The analysis focuses on structural damage, displacement response curves, and acceleration response curves of the UHPC-NC composite column frame structure model and the reinforced frame structure model under the action of a Level 9 frequent earthquake. The following conclusions are drawn:

1. Following the failure of conventional concrete columns, UHPC-NC composite columns exhibit significantly reduced lateral drift stiffness—ranging from 1/4 to 1/10 of the initial stiffness of ordinary concrete columns. This results in enhanced flexibility of the UHPC segmented columns, thereby improving their horizontal deformation capacity and overall seismic performance. These characteristics demonstrate the superior earthquake-resistant properties of this structural design.
2. Under the loading conditions corresponding to the Frequent (Level 7), Design (Level 8), and Rare (Level 9) earthquake intensities, the UHPC-NC composite column frame structure exhibits superior tensile damage performance. Under Level 7 and Level 8 seismic actions, the structure sustains only minor tensile damage. At Level 9 seismic intensity, the base of the ground-floor columns experiences severe tensile damage; however, it remains functional without reaching a failure state. The overall seismic performance of the structure is significantly enhanced.
3. Under the three loading conditions of the El-Centro wave and others, the plastic displacement and inter-story drift angle of the UHPC-NC composite column frame structure are smaller, and the reduction rate of inter-story drift value ranges from 1.68% to 30.87%. Under the action of the three seismic waves, the plastic displacement

and inter-story drift angle have similar patterns, and the seismic performance of the UHPC-NC composite column frame structure is better.

4. Comparing the acceleration response curves at the top of each floor, the overall response of the UHPC-NC composite column frame structure is slightly larger, and its peak acceleration is marginally higher than that of the reinforced frame structure. This shows that the UHPC-NC composite column frame structure exhibits a smaller response under seismic action compared to the reinforced frame structure, which shows a larger response, thus making the UHPC-NC composite column frame structure more advantageous for seismic resistance.
5. Under the loading condition of a Level 9 frequent earthquake, the El-Centro wave, Hyogo-ken Nanbu wave, and KobeEW-020 wave all exhibited similar tensile damage patterns, displacement response curves, and acceleration response characteristics. The UHPC-NC composite column frame structure demonstrated smaller displacement responses and reduced peak displacements.
6. The acceleration response of the UHPC-NC composite column frame structure exhibited larger peak values, faster response times, and greater acceleration during the unloading phase. The inter-story drift angle of the UHPC-NC composite column frame structure was also smaller, indicating superior seismic performance compared to reinforced concrete frame structures.

7. Patents

Chen, B., Luo, Y., Liu, F. C., et al. An Adaptive Seismic-Resistant Composite Column and Its Construction Methodology (In Chinese invention patent) [35]. China National Intellectual Property Administration, Patent Number: ZL202110592200.0.

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Conflicts of Interest: The authors declare no conflicts of interest.

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