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On the Nonlinear Behavior of Composite Structures under Multiple Earthquakes Considering Soil–Structure Interaction

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Abstract: This study investigates the seismic behavior of moment-resistant composite frames with concrete-filled steel tube (CFT) columns and composite steel beams under multiple earthquakes, considering soil–structure interaction (SSI) effects. Nonlinear time history analyses were performed on 2-, 4-, and 6-storey frames under five real seismic sequences and various soil conditions. The key response parameters included interstorey drift ratios, floor displacements, accelerations, and residual deformations. The results indicate that consecutive ground motions generally increase displacement demands and residual deformations compared to single-event scenarios. Incorporating SSI typically reduces drift ratios and accelerations but increases periods and displacements. Contrary to conventional assumptions, taller buildings exhibited lower maximum interstorey drift ratios, with the second storey consistently experiencing the highest drift across all building heights. Peak floor accelerations varied with building height; low-rise structures showed higher accelerations from earthquake sequences, while mid-rise buildings experienced higher accelerations from single events. These findings challenge traditional assumptions in seismic engineering and underscore the importance of considering multiple earthquake scenarios, building-specific factors, and SSI effects in the seismic design of CFT–steel composite frames. The results suggest a need for revising current design approaches to better account for these complex interactions.

Keywords: steel-concrete composite frames; multiple earthquakes; soil–structure interaction; nonlinear behavior

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1. Introduction

Steel members offer high tensile strength and ductility, while concrete members offer high compressive strength and stiffness. Composite members that combine steel and concrete offer the advantages of both materials [1,2]. The most widely used type of composite column is the concrete-filled steel tube (CFT) column (Figure 1), which consists of a steel tube filled with concrete. A CFT column can provide excellent seismic-resistant structural properties, including high strength, ductility, and energy absorption capacity.

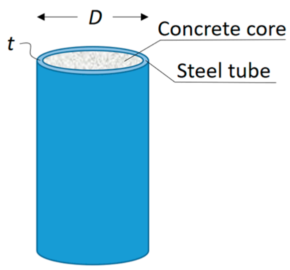

Figure 1. Concrete-filled steel tubes.

In recent years, many studies have been conducted in order to investigate the behavior of CFT columns under seismic loads. Skalomenos et al. [3] examined the nonlinear behavior of square concrete-filled steel tube (CFT) columns subjected to constant axial load and cyclic flexural loading. A detailed finite element model was created, taking into account factors such as cyclic local buckling, the nonlinear behavior of confined concrete, and interface action. The model's accuracy was verified against existing experimental data. A comprehensive parametric study was carried out to establish expressions for three hysteretic models: Bouc–Wen, Ramberg–Osgood, and Al-Bermani. Sixty-four CFT columns with different properties were analyzed under cyclic loading protocols. The calibrated hysteretic models were integrated into the software and compared with experimental and numerical results, allowing for precise simulation of CFT columns in composite moment-resisting frames under cyclic loading. Furthermore, Serras et al. [4] introduced an innovative seismic design strategy for composite structures, specifically focusing on frames featuring circular concrete-filled steel tube (CFT) columns and composite beams. The proposed displacement/damage controlled (DDC) approach enables precise control over structural displacement and damage at different seismic performance levels, even under near-collapse scenarios. This novel method employs empirical equations to forecast the interstorey drift ratio (IDR) and evaluate the damage index (DI) of critical structural components when subjected to specific seismic forces. By doing so, the design process is streamlined, eliminating the necessity for intricate nonlinear time history analyses. The aforementioned studies have significantly advanced the understanding of CFT behavior under cyclic loading. However, they primarily focus on single seismic events, leaving open questions about the cumulative effects of multiple earthquakes on CFT structures.

Seismic analysis and design methods for composite frame structures have undergone extensive development in the past few years. Despite the integration of numerous advancements into modern seismic design codes and the insertion of energy dissipation systems [5,6], they continue to exhibit two certain limitations.

The initial aspect pertains to the soil–structure interaction (SSI) phenomenon. The important effect of SSI is omitted in recent codes but highlighted in the literature. Minasidis et al. [7] examined the impact of soil–structure interaction on the inelastic behavior of two-dimensional steel frames when exposed to near-fault earthquakes, which have been documented in close proximity to seismic faults with reverse and strike-slip mechanisms. A simplified approach to soil–structure interaction was implemented through the use of springs and dashpots to mimic the soil's flexibility at the soil–foundation interface while incorporating the effective properties of the soil. Through dynamic inelastic analyses, seismic response parameters like interstorey drift ratios, maximum floor accelerations, and inelastic displacement ratios were calculated. Following a thorough statistical examination, empirical equations relating these parameters to the number of storeys in structures, the type of fault mechanism, and the presence or absence of soil–structure interaction were derived. The findings highlight the significant influence of soil flexibility on the seismic response of steel frames and emphasize the impact of the fault mechanism on structural response parameters. Another study [8] claimed that experiences from past seismic events like the 1989 Loma Prieta earthquake and the 1995 Kobe earthquake have shown instances where SSI can have a detrimental impact [9]. In engineering practice, ignoring SSI can lead to conservative findings. This disagreement within the research community has led to a lack of well-defined design guidelines. Despite progress in developing solutions for SSI problems, incorporating SSI into design practices remains uncommon. The interplay between soil and structural elements, known as dynamic soil–structure interaction (SSI), presents significant challenges, particularly in relation to the nonlinear properties of soil. The research detailed in Ref. [10] explores how different SSI models influence the evaluation of seismic fragility functions. Initially, a linear substructure methodology was applied, employing two distinct models. The first model was one-dimensional, incorporating a translational elastic spring and a dashpot situated between the foundation node and the ground, with stiffness and viscous damping calculated from the real and imaginary parts of the dynamic impedance at the structure's primary natural frequency. The second model, a more sophisticated Lumped-Parameter Model (LPM), took into account the frequency-dependent characteristics of the impedance. To assess the fragility functions' sensitivity to linearity assumptions, an additional approach that integrates soil nonlinearities was proposed. Furthermore, a different study [11] simulated the nonlinear behavior of soil in the near-field, as well as the dynamic impedance and energy dissipation resulting from radiation damping in the far-field, by consolidating the entire soil–foundation system into a single nonlinear element located at the base of the superstructure. The evaluation of these various methodologies was performed by examining their effects on the characterization of fragility functions for unreinforced masonry structures with pile foundations.

The second issue with modern seismic codes is that they do not take into account the effects of multiple earthquakes. Many regions worldwide experience seismic sequences regularly, causing strains to accumulate at active seismic faults. This leads to a series of ruptures and repeated earthquakes, rather than the immediate release of accumulated strains. The lack of time between successive seismic events often makes it challenging to carry out any rehabilitation efforts due to significant damage accumulation [12]. The research presented in Refs. [13,14] offers a comprehensive analysis of the site characterization and the damage sustained by the Navelli RC Building due to the Central Italy earthquake that occurred on 6 April 2009 (Mw = 6.3). A key finding from their study is that analyses based on ambient noise measurements reveal that the primary structural frequencies observed following the initial damaging event remain consistent over time, suggesting long-term stable structural behavior. In contrast, the strong motion recordings demonstrate that the building displays transient non-stationary behavior, with the fundamental frequency fluctuating during each aftershock, eventually returning to its original value after each event. Hatzigeorgiou and Liolios [12] performed an extensive parametric study focusing on the inelastic response of eight reinforced concrete planar frames subjected to forty-five sequential ground motions. The frames were tested with five real seismic sequences recorded by the same station in the same direction over a short period of time, up to three days. The study [12] highlights the significant damage accumulation resulting from multiple earthquakes, making any rehabilitation efforts impractical. The analysis of the response data leads to important conclusions, indicating that the ground motion sequences play a crucial role in the response and design of reinforced concrete frames. The ductility demands of sequential ground motions can be accurately estimated by combining the demands of individual ground motions. Furthermore, Efraimiadou et al. [15] investigated the impact of pounding between adjacent reinforced concrete building frames during multiple earthquake sequences. The research examined four planar frames and nine pairs of adjacent structures under five real seismic sequences, considering the cumulative damage due to a lack of rehabilitation time between events. The parameters investigated included maximum top floor horizontal displacement, column ductility, and permanent displacements. The study [15] also evaluated four different separation gaps between frames to determine their influence on structural behavior. The research presented in Refs. [16,17] investigates the acceleration requirements in low-rise reinforced concrete (RC) buildings subjected to torsional effects. The primary objective was to quantify peak floor accelerations (PFAs) and floor response spectra (FRS). This study sought to develop straightforward empirical formulas to assess the amplification effects linked to torsion, which may be considerable in both existing and newly constructed RC structures. In the work of Katsimpini [18], the seismic response of asymmetrical mixed concrete–steel frames was examined, focusing on soil–structure interaction and structural irregularity. Nonlinear time history analyses were conducted using far-fault earthquakes and seismic sequences. The findings reveal that soil–structure interaction increases fundamental periods and generally reduces seismic demands in three-storey frames. Irregular mixed frames exhibit higher floor accelerations than regular frames. Sequential ground motions increase displacement demands compared to single events, affecting permanent displacements on both rigid and deformable soil. The findings emphasize the greater detrimental effects of seismic sequences on structures compared to single seismic events, highlighting the importance of considering multiple earthquake scenarios in structural design and assessment.

This research examines the seismic performance of concrete-filled tube (CFT) structures with varying heights under multiple earthquake events. The study focuses on two-, four-, and six-storey CFT buildings subjected to five authentic seismic sequences, all recorded at a single station within a 72-hour timeframe. Using nonlinear time history analysis, the research team computes the dynamic responses of these two-dimensional structures, considering both fixed-base conditions and soil–structure interaction (SSI) effects. The investigation centers on key structural indicators, including peak and residual displacements and interstorey drift ratios. The study's dual approach, examining both fixed-base and SSI scenarios, offers valuable insights into how foundation flexibility influences the structures' earthquake resistance. By analyzing the computational results, the research team draws significant conclusions about CFT building behavior during multiple seismic events. These findings contribute to the advancement of design practices for these increasingly prevalent structural systems, potentially enhancing their resilience against complex earthquake scenarios. By combining the analysis of multiple earthquake effects with SSI considerations, this study offers a novel approach to understanding the seismic behavior of CFT structures. The produced findings have the potential to inform more resilient design practices for these increasingly popular structural systems, particularly in regions prone to seismic sequences. The following sections detail the methodology, present selected results, and discuss their implications for seismic engineering practice and future research directions.

2. Description and Design of Composite Structures

In this study, 2-, 4-, and 6-storey frames are examined (Figure 2). The floor height is equal to 3.0 m. The frames consist of two bays, and each bay has a span of 6 m. The structural frames in this study are designed in accordance with Eurocode-3 [19], Eurocode-4 [20], and Eurocode-8 [21] standards, utilizing SAP2000 [22]. Two load combinations are considered: a seismic combination and a gravity combination, according to Eurocode 8 [21]. The seismic load combination incorporates a vertical load of 25 kN/m on the beams, calculated as G + 0.3Q + E, where G is the dead load plus 0.3 times the live load (Q), in addition to the earthquake load (E). The gravity load combination applies a total load of 42 kN/m, calculated as 1.35G + 1.5Q.

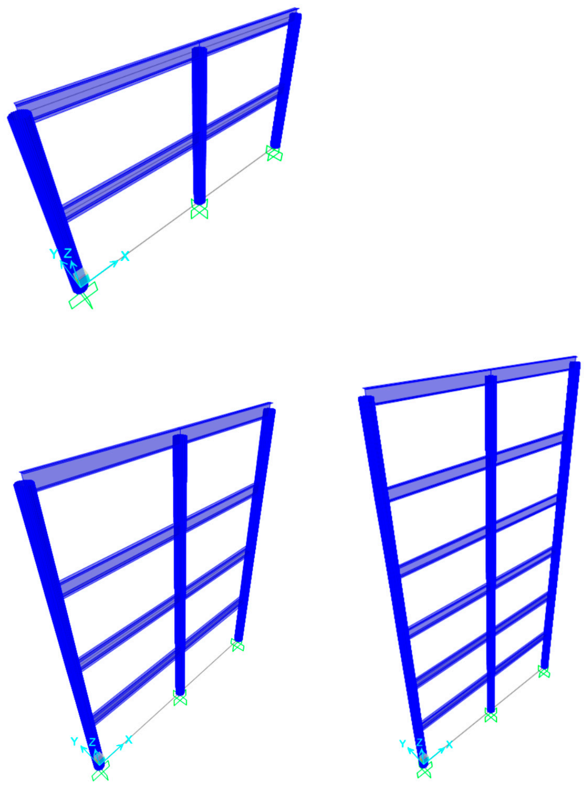

Figure 2. Cross-section of a concrete-filled steel tube and 2-, 4-, and 6-storey frames in SAP2000 [22].

For each floor, dead loads are set at 20 kN/m, while live loads are 10 kN/m. The design incorporates a ground acceleration of 0.24 g and a behavior factor (q) of 4.0, consistent with medium structural ductility and Spectrum Type 1 requirements. The behavior factor, q, is in accordance with the provisions of §5.2.2.2 of EC8 [21]. The design also accounts for the self-weight of beams and slabs within the dead load calculations.

The frames under study consist of circular concrete-filled steel tube (CFT) columns (Figure 1) and steel beams connected with concrete floor slabs. Table 1 shows the sectional dimensions of the examined frames, considering the yield steel stress of 275 MPa and the compressive concrete strength of 25 MPa.

Table 1. Sectional dimensions of columns and beams for the 2-, 4-, and 6-storey structures.

Number of Storeys	Column	Beam
2	D = 406.4 mm, t = 6.3 mm	IPE400
4	D = 559 mm, t = 10 mm	IPE500
6	D = 610 mm, t = 14.2 mm	IPE550

3. Modeling of the Composite Structures

The behavior of composite columns is modeled using the modified Ramberg–Osgood model, according to Serras [23]. The Ramberg–Osgood model is employed to characterize load-displacement hysteresis curves, H-Δ, which exhibit an elastic portion up to the yield displacement Δy and the corresponding yield force Hy(=Fy), followed by a transition curve leading to a plastic state, as indicated in Figure 3. The transition from elastic to plastic behavior is influenced by the Ramberg–Osgood factor r2, as demonstrated in Figure 3. Serras [23] introduced a simple yet effective analytical model for the cyclic behavior and strength capacity of circular concrete-filled steel tube (CFT) columns under axial load and cyclically varying flexural loading. Based on this databank, empirical expressions are formulated to assess the phenomenological parameters of the well-known Ramberg–Osgood hysteretic model. Furthermore, empirical analytical relations are established to provide a direct and efficient representation of the ultimate strength of circular CFT columns, which are then validated. The inelastic behavior of the structure is analyzed by considering the potential formation of plastic hinges at the extremities of each member, which can be described using a bi-linear hysteresis mode. Regarding the modeling of nonlinearities of CFT columns in SAP2000, user-defined hinges that follow the modified Ramberg–Osgood hysteretic behavior are introduced. The nonlinear behavior of steel beams is modeled using plastic hinges that consider the number of cycles for the degradation of strength. More details can be found in the work of Kamaris et al. [24]. Diaphragm action is utilized to model the presence of composite slabs. It is expected that the composite floor slab diaphragms will transfer in-plane shear forces generated by earthquakes to the lateral load-resisting system. The distribution of these forces within a structure is contingent upon the diaphragm's stiffness and strength.

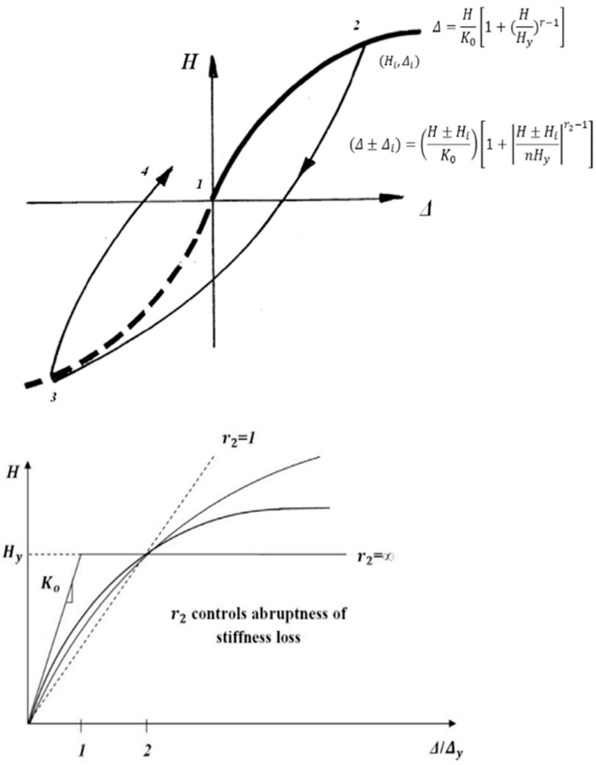

Figure 3. Surface of the Ramberg–Osgood model (**top**) and the r2 factor (**bottom**) [23].

4. Ground Motions and Soil–Structure Interaction Modeling

The comprehensive ground motion database utilized in this analysis consists of five genuine seismic sequences. These sequences were recorded over a limited duration, lasting up to three days, by the same station, in a consistent direction, and at nearly identical distances from the fault. The seismic sequences include the Mammoth Lakes (May 1980–5 events), Chalfant Valley (July 1986–2 events), Coalinga (July 1983–2 events), Imperial Valley (October 1979–2 events), and Whittier Narrows (October 1987–2 events) earthquakes. In Table 2, a thorough listing of the five seismic sequences employed in the analysis is provided. These sequences were captured by the Pacific Earthquake Engineering Research (PEER) Center [25]. The table encompasses the following details for each seismic sequence: the name of the earthquake event, the name of the strong motion recording station, the component of the ground motion record, the date and time of the earthquake event, the local magnitude (ML), the Arias intensity (Ia) of the ground motion, and the recorded peak ground acceleration (PGA).

The Arias intensity (Ia) is a significant parameter in earthquake engineering as it quantifies the cumulative energy content of a ground motion record. It is calculated by integrating the square of the acceleration over the duration of the record, scaled by a constant factor ($\pi/2g$).

These records are regarded as appropriate for soil class B, thereby adhering to the design process described in the previous section. Each sequential ground motion record from the PEER database is integrated into a unified ground motion record (serial array), with a time interval of 100 s applied between consecutive seismic events. This interval maintains zero acceleration ordinates, effectively preventing any structural movement due to damping. For the sake of compatibility with the design process, the seismic sequences are adjusted to ensure a maximum peak ground acceleration (PGA) of 0.24 g. Figure 4 depicts the response spectra for these records.

Table 2. Seismic sequences examined in this study.

No.	Seismic Sequence	Station	Component	Date (Time)	Magnitude (ML)	Ia (m/s)	Recorded PGA(g)
1	Mammoth Lakes	54099 Convict Creek	N-S	25 May 1980 (16:34)	6.1	2.619	0.442
				25 May 1980 (16:49)	6.0	0.1967	0.178
				25 May 1980 (19:44)	6.1	0.348	0.208
				25 May 1980 (20:35)	5.7	1.088	0.432
				27 May 1980 (14:51)	6.2	0.511	0.316
2	Chalfant Valley	54428 Zack Brothers Ranch	E-W	20 July 1986 (14:29)	5.9	0.526	0.285
				21 July 1986 (14:42)	6.3	1.932	0.447
3	Coalinga	46T04 CHP	N-S	22 July 1983 (02:39)	6.0	0.826	0.605
				25 July 1983 (22:31)	5.3	1.448	0.733
4	Imperial Valley	5055 Holtville P.O.	HPV315	15 October 1979 (23:16)	6.6	0.841	0.221
				15 October 1979 (23:19)	5.2	0.1340	0.211
5	Whittier Narrows	24401 San Marino	N-S	1 October 1987 (14:42)	5.9	0.303	0.204
				4 October 1987 (10:59)	5.3	0.175	0.212

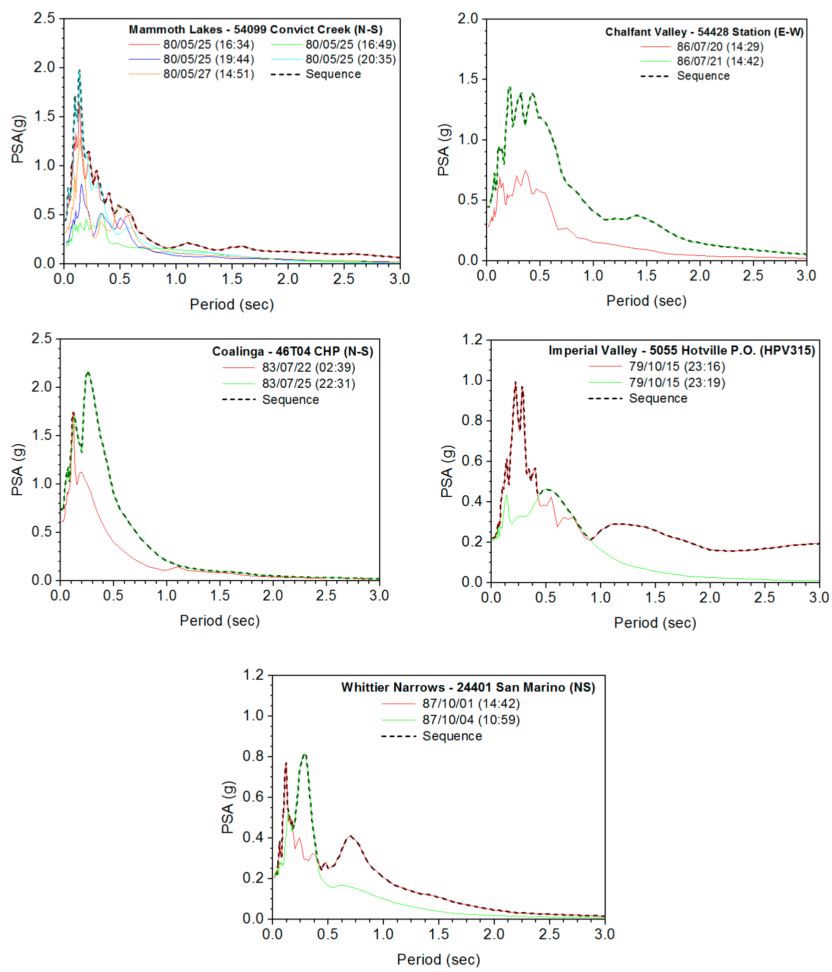

Figure 4. Response spectra of the examined seismic sequences.

In order to simulate soil–structure interaction, the foundation is depicted as a set of separate springs and dashpots that are not influenced by frequency [26]. Mulliken and Karabalis [26] proposed a detailed discrete model aimed at predicting dynamic interactions occurring through the soil between neighboring rigid surface foundations, which rest on a homogeneous, isotropic, and linear elastic half-space. The interaction between the foundations via the soil is facilitated by the establishment of frequency-independent stiffness and damping functions, which connect the degrees of freedom across the entire foundation system. The dynamic analysis of this interconnected system is performed in the time domain, incorporating the time-lagging effects of the coupled dynamic input due to wave propagation and employing a modified version of the Wilson-θ method. Additionally, the foundational interaction model is extended to evaluate coupled building–foundation systems, taking into account both horizontal and vertical movements of the foundation as well as its rocking motion. The system of springs, dashpots, and masses is simulated using the 'Link element' [22], as shown in Figure 5. In the case of a 2-storey frame, each concrete column is based on a 1.5 m × 1.5 m × 0.6 m footing, designed in compliance with Eurocode 8 [21] standards. The 4-storey frame is founded on a 1.75 m × 1.75 m × 0.8 m footing, and the footing of the 6-storey frame has dimensions of 2 m × 2 m × 1 m.

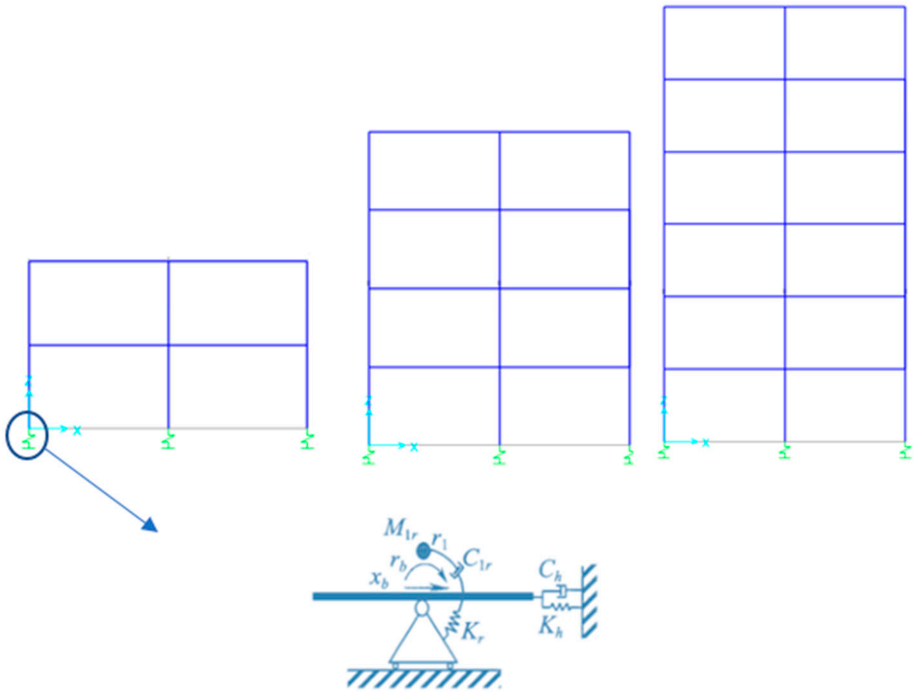

Figure 5. 2D frame structures with Link elements [22].

The soil is categorized as type C, with a shear wave velocity of 270 m/s and a density of 1900 kg/m^3. To take into account soil nonlinearity during high ground accelerations, the effective shear modulus is decreased to 50% of its initial 'elastic' value.

The coefficients of springs and damping coefficients of dashpots are presented in Tables 3–5 for the 2-, 4-, and 6-storey buildings, respectively, and they are obtained from the following equations:

$$K_v = \frac{4.7G_0a}{1-v} \tag{1}$$

$$K_H = \frac{9.2G_0a}{2-v} \tag{2}$$

$$K_R = \frac{4G_0a^3}{1-v} \tag{3}$$

$$C_v = \frac{0.8a}{V_s}K_v \tag{4}$$

$$C_H = \frac{0.163a}{V_s}K_H \tag{5}$$

$$C_R = \frac{0.6a}{V_s} K_R \quad (6)$$

where the parameter a represents half the width of each column's square foundation. Additionally, G_0 and ν denote the soil's shear modulus and Poisson's ratio, respectively, and V_s indicates the soil's shear wave velocity.

Table 3. SSI coefficients for the 2-storey frame.

Direction/Motion	Spring Coefficient (kN/m)	Dashpot Coefficient (kNs/m)
Vertical	348,748,392.86	1,096,010.46
Horizontal	281,093,823.53	179,991.25
Rocking	166,954,017.86	393,514.39

Table 4. SSI coefficients for the 4-storey frame.

Direction/Motion	Spring Coefficient (kN/m)	Dashpot Coefficient (kNs/m)
Vertical	406,873,125	1,491,792.02
Horizontal	327,942,794.12	244,988.10
Rocking	265,116,796.88	729,033.99

Table 5. SSI coefficients for the 6-storey frame.

Direction/Motion	Spring Coefficient (kN/m)	Dashpot Coefficient (kNs/m)
Vertical	464,997,857.14	1,948,463.04
Horizontal	374,791,764.71	319,984.45
Rocking	395,742,857.14	1,243,699.81

5. Results

In this study, the structures are analyzed through a nonlinear time history, employing sequential ground motion records. The research is centered on significant structural parameters, which encompass peak and residual displacements as well as interstorey drift ratios. The evaluation of the seismic response considers important factors, including the implications of soil–structure interaction (SSI), and reviews frames with differing heights.

5.1. Fundamental Periods of the Structures under Consideration

The fundamental period of the building structures being studied is examined in the following table. Table 6 displays the fundamental period of the structures for fixed and deformable soil. It is obvious that the insertion of Link elements enlarges the fundamental period.

Table 6. Fundamental periods of the structures under study.

Number of Storeys	Case	T_1 (s)
2	Fixed	0.358
2	SSI	0.406
4	Fixed	0.541
4	SSI	0.586
6	Fixed	0.789
6	SSI	0.890

5.2. Interstorey Drift Ratio

In recent years, there has been a significant surge in interest in structural health monitoring (SHM) among academic researchers and professional engineers alike. In two studies [27,28], the modal curvature evaluation technique was presented and aimed at detecting and localizing damage in framed structures while considering the changes in mode curvature that occur due to severe seismic activity. They also presented a methodology for localizing damage in framed structures subjected to strong motion earthquakes, focusing on the monitoring of modal curvature variations in the natural frequency of the structure [29,30]. The interstorey drift ratio (IDR) is a key measurement that represents the relative horizontal displacement between two consecutive floors, divided by the height of a storey. This value is commonly presented as a percentage or a ratio. The IDR plays a critical role because it signifies the extent of deformation that a building undergoes during seismic events. Additionally, it aids engineers in assessing the likelihood of both structural and non-structural harm. Moreover, the IDR is utilized in construction regulations to establish seismic performance design thresholds. It has been determined that an IDR value of less than 1% indicates damage to non-structural components, whereas values greater than 4% may indicate irreversible structural damage or collapse [31].

Figure 6 presents the maximum interstorey drift ratio of the 2-storey structure under single and sequential ground motion. It is interesting to note that this analysis has uncovered instances where a single seismic event resulted in a higher interstorey drift ratio (IDR) compared to a full sequential earthquake scenario. This unexpected outcome may be due to various factors: (i) Characteristics of the specific ground motions: The frequency content of the single event may closely match the natural frequency of the structure, leading to resonance and larger displacements; (ii) Energy dissipation: The initial event in a sequence may cause the structure to dissipate energy through minor damage or nonlinear behavior, potentially making it more resilient to subsequent shocks. This observation emphasizes the complexity of structural responses to seismic sequences and highlights the importance of considering both single and multiple event scenarios in seismic design.

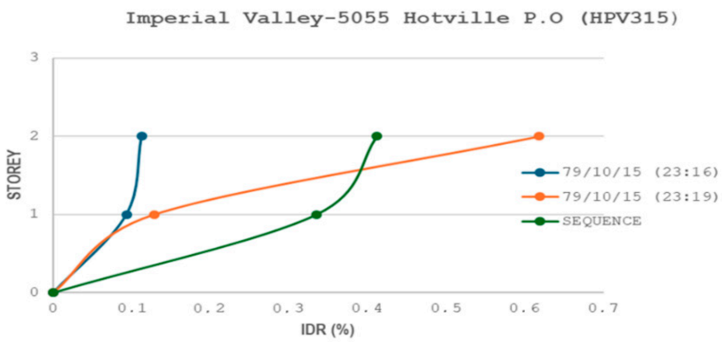

Figure 6. Maximum interstorey drift ratios (IDRs) under single and sequential ground motions (2-storey building founded on stiff soil).

Figures 7 and 8 present the maximum interstorey drift ratio of the 4- and 6-storey structures, respectively, under single and sequential motion. These plots reveal an unexpected trend: the maximum interstorey drift ratio (IDR) decreases as building height increases, with 6-storey structures showing a lower IDR than 2-storey ones and 4-storey buildings exhibiting a lower IDR than 2-storey structures. This counterintuitive finding can be explained by several factors. Taller buildings have greater total mass, increasing inertial resistance to lateral forces. Their longer natural periods may lead to lower spectral accelerations for many earthquakes. The design of taller buildings often incorporates more efficient lateral force-resisting systems, which may be overdesigned for lower heights but become more effective as building height increases. Furthermore, taller buildings are more influenced by higher-mode shapes during seismic events, potentially leading to a more complex distribution of interstorey drifts. This observation underscores the complex relationship between building height and seismic response, highlighting the importance of considering structural dynamics in seismic design across various building heights. The specificity of this result is significant, arising from the fact that the six-storey buildings are more effectively designed than their two-storey counterparts, which also exhibit different dynamic properties.

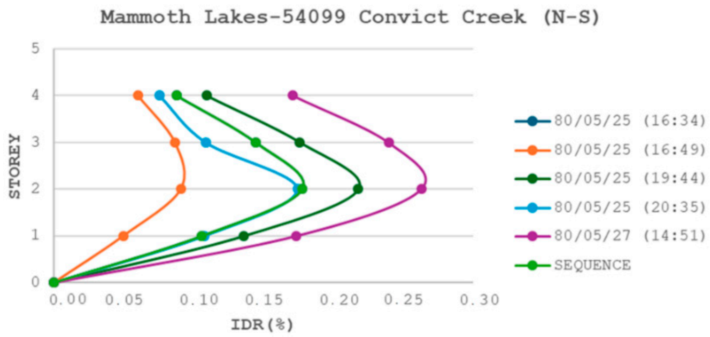

Figure 7. Maximum interstorey drift ratios (IDRs) under single and sequential ground motions (4-storey building founded on stiff soil).

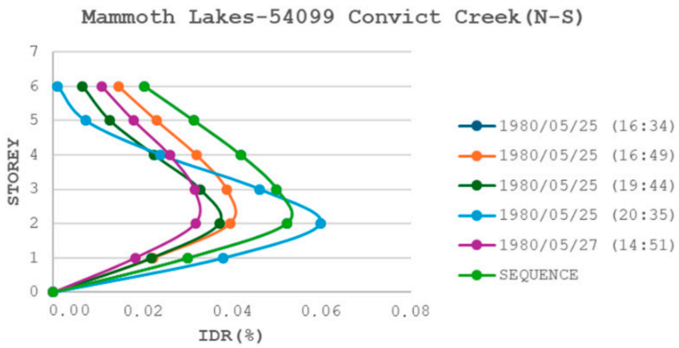

Figure 8. Maximum interstorey drift ratios (IDRs) under single and sequential ground motions (6-storey building founded on stiff soil).

The study of 2-, 4-, and 6-storey structures reveals surprising patterns in interstorey drift ratio (IDR) behavior under both fixed-base and soil–structure interaction (SSI) conditions. Unexpectedly, the IDR values remain notably consistent between fixed-base and SSI scenarios across all examined building heights. This consistency challenges prevailing assumptions about SSI's impact on structural response during seismic events.

Figures 9 and 10 present the maximum interstorey drift ratio of the 2- and 6-storey structures, respectively, under single and sequential motion, considering SSI effects. A striking observation is that single earthquake events consistently yield higher IDR values compared to multiple earthquake sequences. This holds true regardless of SSI consideration and applies uniformly across all building heights studied. Such findings contradict the common expectation that cumulative effects from multiple seismic events would result in more significant drift ratios.

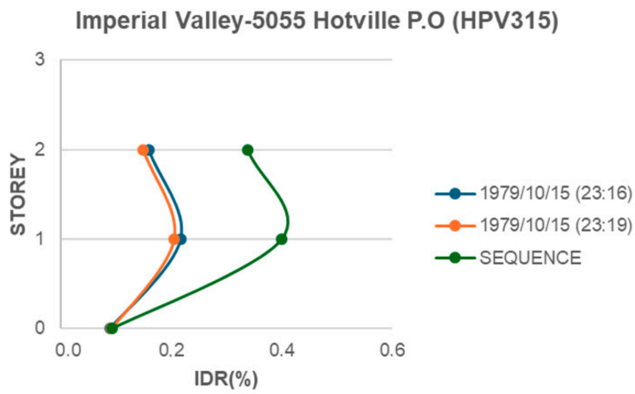

Figure 9. Maximum interstorey drift ratios (IDRs) under single and sequential ground motions (2-storey building founded on compliant soil).

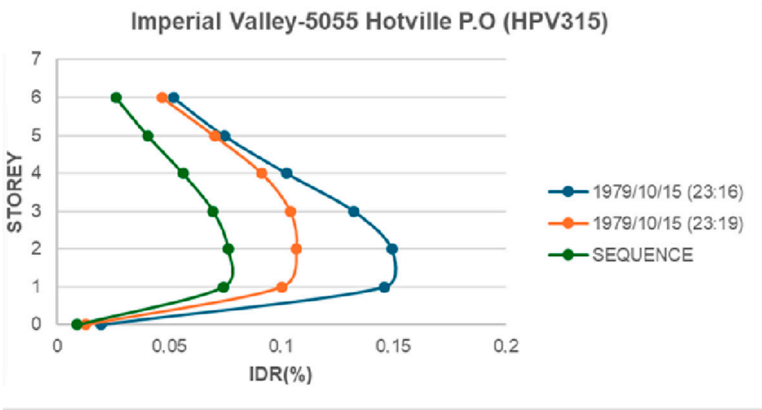

Figure 10. Maximum interstorey drift ratios (IDRs) under single and sequential ground motions (6-storey building founded on compliant soil).

The uniformity of this behavior across varying building heights, with or without SSI, points to a more intricate structural response to seismic forces than is typically assumed. It emphasizes the necessity for a more sophisticated approach to understanding building reactions to both isolated and sequential seismic events, as well as the nuanced role of soil–structure interaction.

The analysis also reveals a consistent pattern across all studied structures: the second storey consistently experiences the maximum interstorey drift ratio (IDR), regardless of overall building height. This phenomenon can be explained by several structural and dynamic factors. Lower stories in multi-storey buildings typically face higher shear forces from lateral loads. However, the ground floor's connection to the foundation provides additional stiffness, limiting its movement. The second storey, while still subject to high shear forces, lacks this extra restraint, making it more prone to lateral displacement. Furthermore, the second storey marks a crucial point where the combined mass of the upper floors begins to significantly impact the building's response, yet overall stiffness is reduced compared to the base. This creates a 'weak storey' effect, focusing deformations and resulting in higher IDR values in the second storey across all building heights examined.

These results highlight the importance of conducting thorough seismic analyses that account for diverse scenarios rather than relying on simplified assumptions about SSI effects or the impacts of multiple earthquakes. This research underscores the complexity of seismic structural behavior and the need for comprehensive, multi-faceted approaches in seismic design and analysis.

5.3. Residual Interstorey Drift Ratio

The RIDR (residual interstorey drift ratio) is a key measure in earthquake engineering that quantifies the permanent lateral displacement between adjacent floors in a building after a seismic event. It helps engineers assess a structure's post-earthquake integrity and functionality. The RIDR is calculated as the ratio of residual displacement to storey height, typically expressed as a percentage or in radians. This concept is vital for several reasons: (i) it aids in evaluating building safety and stability after earthquakes; (ii) it helps predict repair costs and downtime; (iii) it informs seismic design codes and performance-based design approaches; and (iv) it contributes to developing resilient structures and effective retrofitting strategies.

It has been observed in the research of Hatzigeorgiou and Liolios [12] that the presence of multiple earthquakes has a significant impact on permanent displacements, highlighting the necessity of accounting for multiple earthquake occurrences to ensure reliable estimates of permanent displacements. Their results demonstrate the effects on structures subjected to both real and artificial seismic events, illustrating the temporal evolution of horizontal displacements at the top of these structures. The continuous accumulation of permanent displacement is clearly visible in all scenarios examined.

Figures 11–13 present the residual interstorey drift ratio of the 2-, 4-and 6-storey structure, respectively, founded on stiff soil, under single and sequential motion. Figures 14 and 15 present the residual interstorey drift ratio of the 2-and 6-storey structure, respectively, founded on compliant soil, under single and sequential motion. Analysis of the residual interstorey drift ratio (RIDR) across 2-, 4-, and 6-storey buildings reveals unexpected trends that challenge conventional wisdom in seismic engineering. The data present a counterintuitive scenario where the effects of soil–structure interaction (SSI) on residual deformations appear less significant than traditionally assumed. A striking revelation is the comparable RIDR values observed between fixed-base and SSI conditions across all building heights. This similarity suggests that the inclusion of SSI in the analysis may not dramatically alter predictions of post-earthquake residual deformations, as previously thought. Perhaps most surprisingly, single seismic events often yield higher RIDR values compared to multiple earthquake sequences. This pattern persists regardless of building height or the consideration of SSI, defying the logical expectation that cumulative damage from sequential events would result in greater residual deformations.

The consistency of these observations across varying structural configurations points to a more complex interplay between seismic loading, structural response, and residual deformations than current models might suggest. It highlights potential gaps in our understanding of how buildings retain deformation after single versus multiple seismic events and how soil–structure interaction influences this process.

These findings underscore the need for a reevaluation of current seismic design approaches. They suggest that reliance on simplified assumptions about SSI effects or the impacts of multiple earthquakes may lead to overly conservative or potentially unconservative designs. Moving forward, a more nuanced and comprehensive approach to seismic analysis and design may be necessary, one that can account for the complex and sometimes counterintuitive behavior of structures under various seismic scenarios.

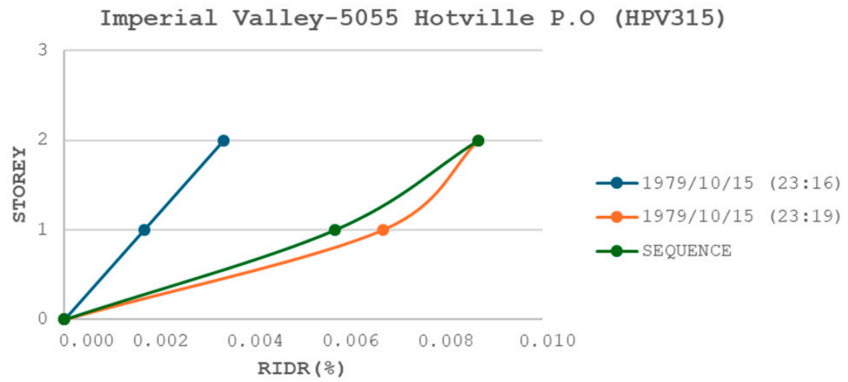

Figure 11. Residual interstorey drift ratios (RIDRs) under single and sequential ground motions (2-storey building founded on stiff soil).

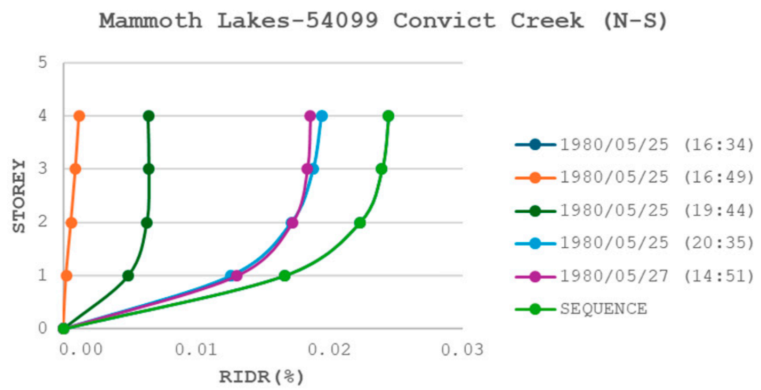

Figure 12. Residual interstorey drift ratios (RIDRs) under single and sequential ground motions (4-storey building founded on stiff soil).

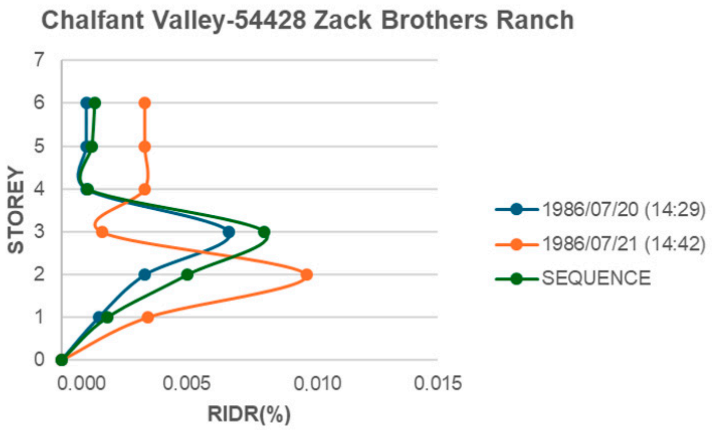

Figure 13. Residual interstorey drift ratios (RIDRs) under single and sequential ground motions (6-storey building founded on stiff soil).

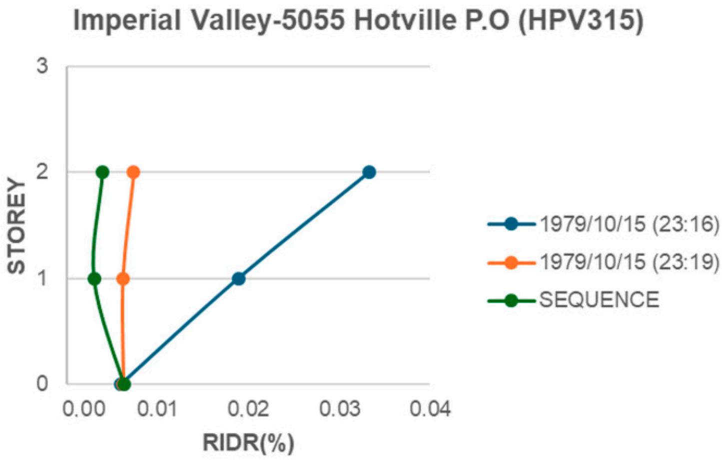

Figure 14. Residual interstorey drift ratios (RIDRs) under single and sequential ground motions (2-storey building founded on compliant soil).

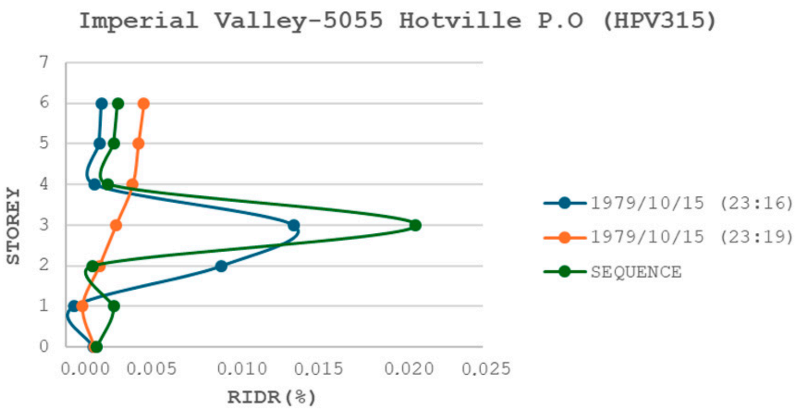

Figure 15. Residual interstorey drift ratios (RIDRs) under single and sequential ground motions (6-storey building founded on compliant soil).

5.4. Peak Floor Acceleration

Floor-level horizontal accelerations are crucial for designing diaphragms, their connections, and non-structural elements in buildings. Earthquakes have been known to produce significant horizontal accelerations at floor levels, leading to inertial forces that can damage building services and, in severe cases, cause structural failure or collapse [32,33]. Studies have presented an analytical examination of floor-level horizontal accelerations occurring in regular buildings with rigid diaphragms during seismic events [33,34].

The response of buildings to seismic events varies significantly based on their height, with intriguing differences observed between low-rise and mid-rise structures. In 2-storey buildings, a sequence of earthquakes tends to produce higher peak floor accelerations compared to a single seismic event (Figure 16). This phenomenon likely stems from the cumulative effects of multiple shocks, which can progressively weaken the structure and potentially create resonance conditions that amplify structural responses.

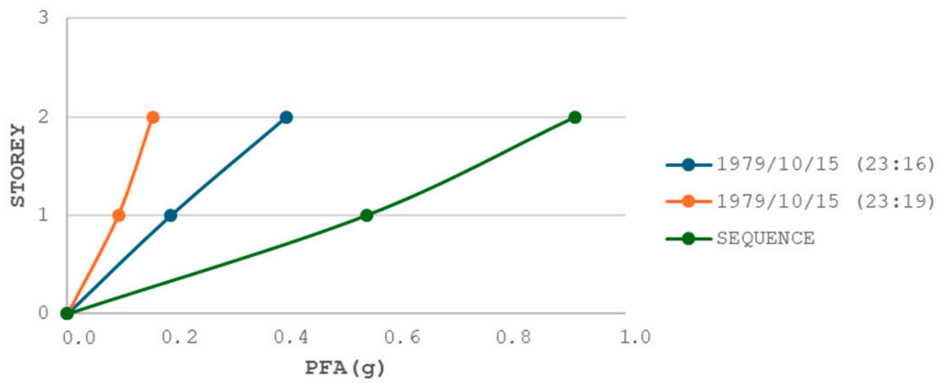

Figure 16. Peak floor acceleration (PFA) under single and sequential ground motions (2-storey building founded on stiff soil).

Conversely, 4- and 6-storey buildings exhibit an opposite trend, where single earthquake events generally induce higher peak floor accelerations than a series of shocks, as shown in Figures 17 and 18. This difference may be attributed to the more complex dynamic behavior of taller structures, including the influence of higher vibration modes. In these buildings, a single strong event might more effectively excite critical modes of vibration, leading to higher peak accelerations. Figures 19 and 20 present the peak floor acceleration of the 2- and 6-storey structure, respectively, founded on compliant soil, under single and sequential motion.

Interestingly, these patterns persist regardless of whether the building foundation is modeled as fixed or if soil–structure interaction (SSI) effects are considered. While SSI does not fundamentally alter these trends, it does influence the overall structural response. SSI allows for energy dissipation through the soil and can modify a building's natural frequency, potentially mitigating some seismic effects.

The persistence of these trends across different foundation modeling approaches underscores the complex nature of seismic structural dynamics. It highlights the intricate interplay between factors such as building height, the characteristics of seismic sequences, and soil–structure interaction.

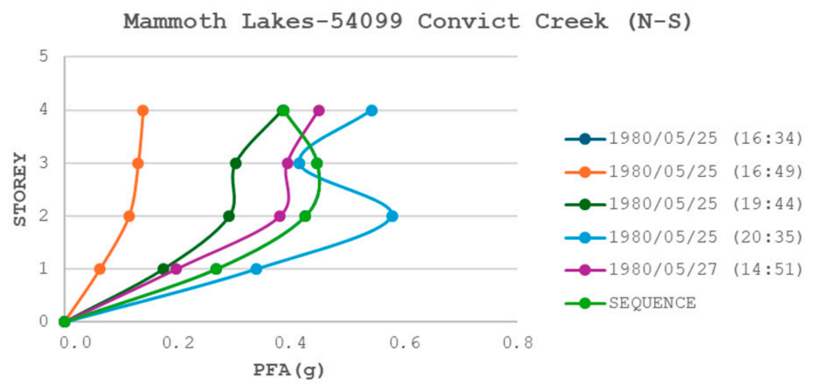

Figure 17. Peak floor acceleration (PFA) under single and sequential ground motions (4-storey building founded on stiff soil).

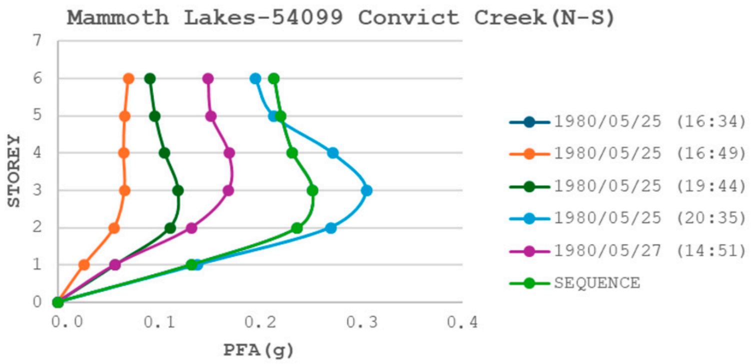

Figure 18. Peak floor acceleration (PFA) under single and sequential ground motions (6-storey building founded on stiff soil).

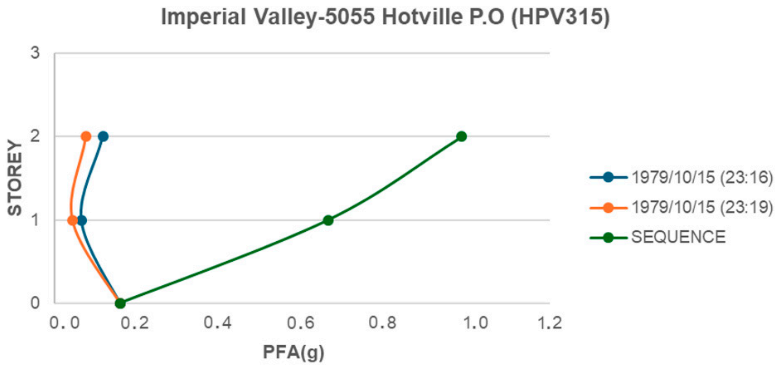

Figure 19. Peak floor acceleration (PFA) under single and sequential ground motions (2-storey building founded on compliant soil).

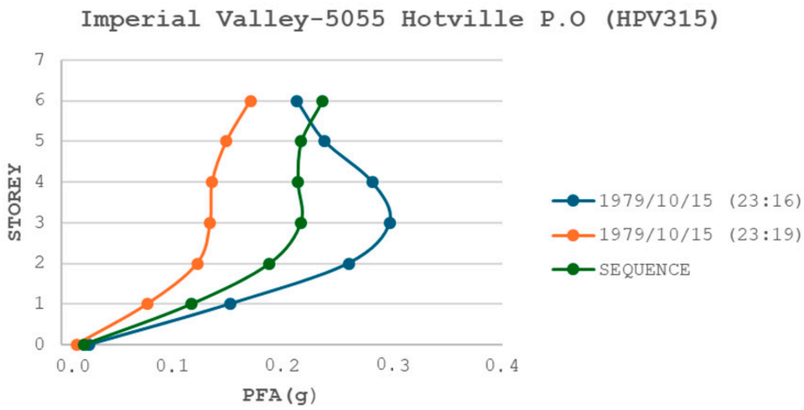

Figure 20. Peak floor acceleration (PFA) under single and sequential ground motions (6-storey building founded on compliant soil).

These observations have significant implications for seismic design and analysis. They emphasize the need for height-specific considerations in building design and the importance of accounting for both single events and seismic sequences. Furthermore, they underscore the value of incorporating SSI effects in seismic analysis to achieve a more comprehensive understanding of structural behavior during earthquakes.

6. Analyzing the Structural Response: Comparing Stiff and Compliant Soil Conditions

The examination conducted in this study regarding moment-resistant composite frames featuring concrete-filled steel tube (CFT) columns and composite steel beams has produced several noteworthy findings related to their structural performance across various soil conditions. Figures 21–26 facilitate a clear comparison of essential response parameters between frames situated on stable soil and those positioned on softer soil.

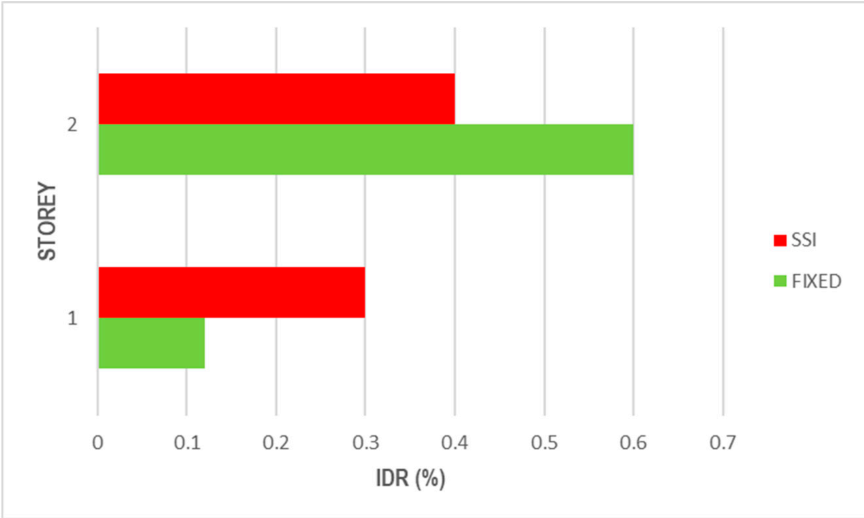

Figure 21. Interstorey drift ratios (IDRs) of 2-storey frames founded on stiff and compliant soil, respectively.

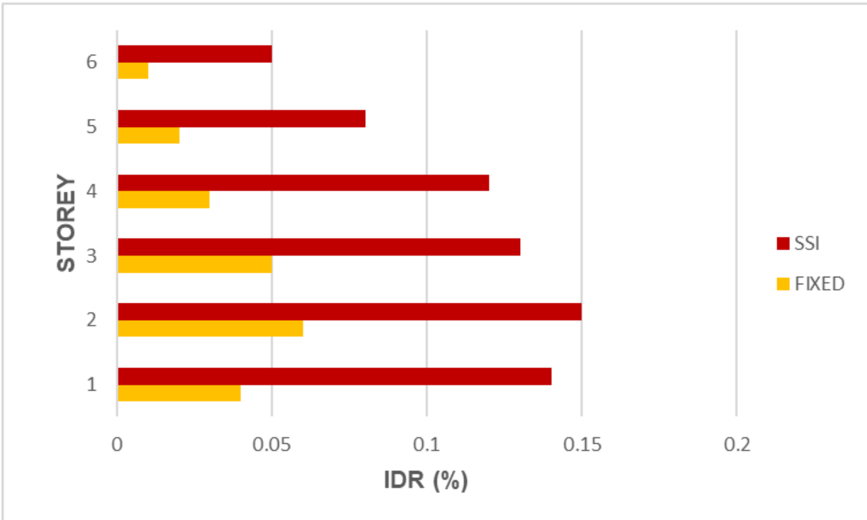

Figure 22. Interstorey drift ratios (IDRs) of 6-storey frames founded on stiff and compliant soil, respectively.

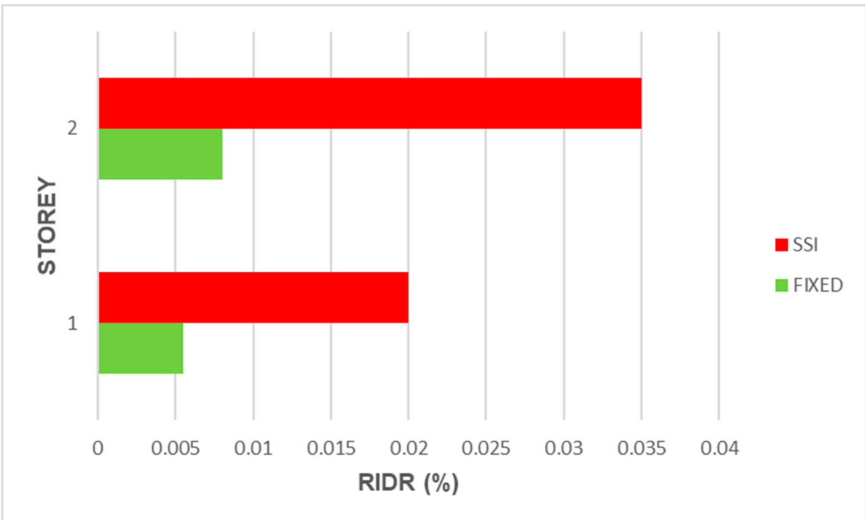

Figure 23. Residual interstorey drift ratios (RIDRs) of 2-storey frames founded on stiff and compliant soil, respectively.

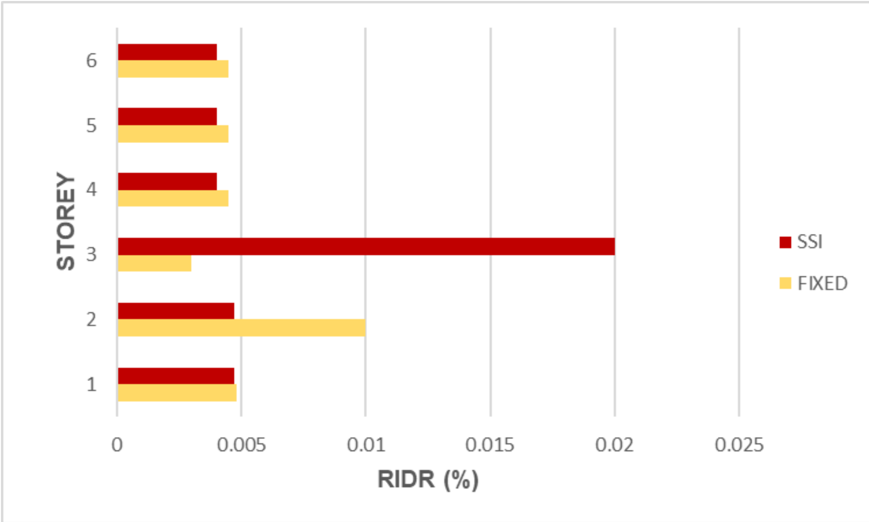

Figure 24. Residual interstorey drift ratios (RIDRs) of 6-storey frames founded on stiff and compliant soil, respectively.

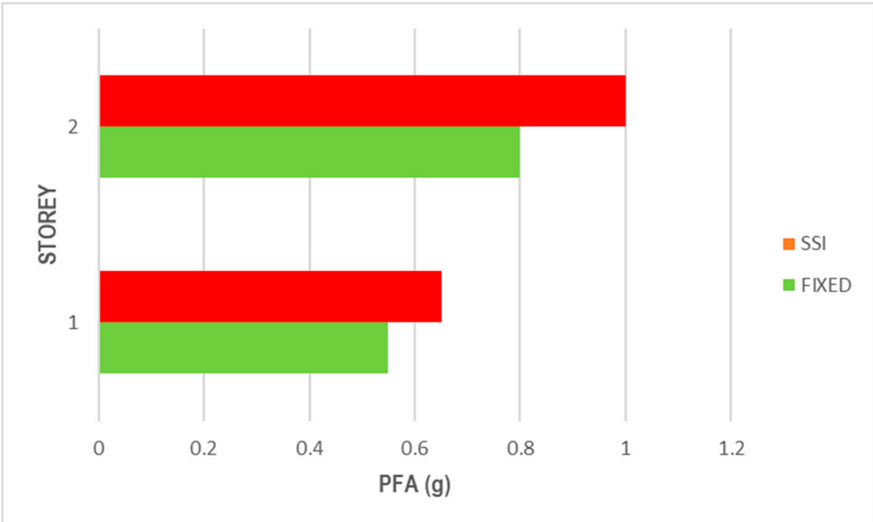

Figure 25. Peak floor acceleration (PFA) of 2-storey frames founded on stiff and compliant soil, respectively.

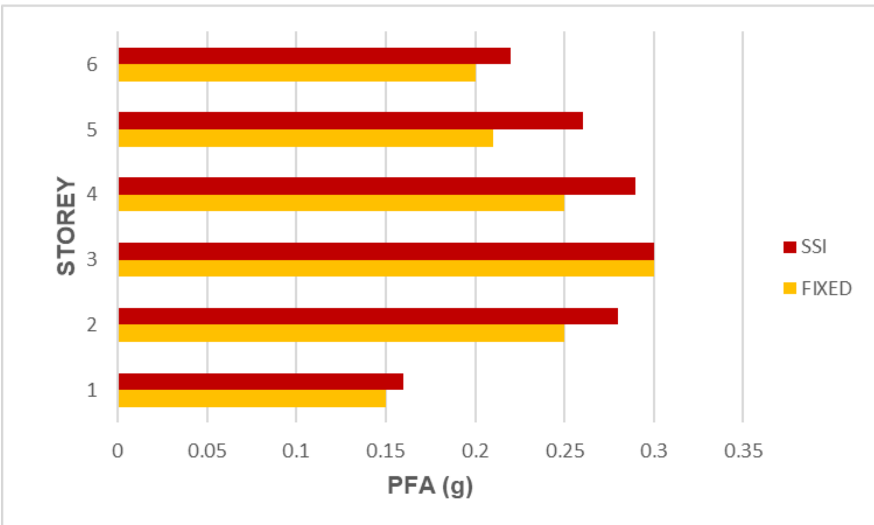

Figure 26. Peak floor acceleration (PFA) of 6-storey frames founded on stiff and compliant soil, respectively.

The results illustrated in Figures 21 and 22 indicate that incorporating soil–structure interaction (SSI) effects generally resulted in a reduction in the maximum interstorey drift ratios for both the 2-storey and 6-storey frames, irrespective of whether the structures faced single or sequential earthquake occurrences. This observation implies that the flexibility of the compliant soil contributes to energy dissipation and limits the lateral deformations that the structures undergo.

The examination of Figures 23 and 24 suggests that the soil conditions had a limited effect on the residual interstorey drift ratios (RIDRs). The RIDR values were largely consistent between the frames on stiff and compliant soil, respectively, thereby contradicting the common assumption that soil–structure interaction (SSI) would have a profound impact on the permanent deformations of the structures.

Figure 22 indicates that the two-storey frame on compliant soil exhibited lower peak floor accelerations than the frame on stiff soil in both single and sequential earthquake scenarios. Conversely, the trend was not as clearly defined for the 6-storey frame, as shown in Figure 26. The taller structure revealed PFA values that were more aligned across various soil conditions, suggesting that the impact of soil–structure interaction (SSI) on floor accelerations could be more nuanced and dependent on the height of the structure.

The interaction between soil and structural components can positively influence the management of interstorey drift ratios in CFT structures. However, its impact on residual deformations may not be as significant as is often assumed. The effect of soil conditions on peak floor accelerations is particularly pronounced in shorter buildings, whereas taller structures demonstrate a more intricate response that is less directly associated with soil flexibility. These observations underscore the essential importance of considering both single and multiple earthquake events, as well as specific building characteristics such as height, when assessing the seismic performance of CFT structures in various soil environments.

7. Conclusions

The analysis of concrete-filled steel tube (CFT) structures in this study has led to several key conclusions:

- Seismic Sequences versus Single Events: Typically, the occurrence of several earthquakes leads to increased displacement demands and more significant residual deformations than those observed in single seismic events. Nevertheless, there have been instances where individual earthquakes have resulted in larger interstorey drift ratios, thereby questioning the traditional belief that seismic sequences invariably cause more severe structural reactions.
- Soil–Structure Interaction (SSI) Effects: It is commonly anticipated that soil–structure interaction will diminish drift ratios and accelerations while extending periods and displacements. Nevertheless, its impact on residual drift ratios has proven to be less significant than previously assumed. Both fixed-base and SSI models displayed comparable residual drift ratios, which contradicts the prevalent belief that soil flexibility would markedly influence the permanent deformations of structures.
- Building Height and Response: Contrary to established assumptions, taller buildings exhibited lower maximum interstorey drift ratios. This occurrence may be attributed to factors such as increased mass and more effective lateral force-resisting systems found in taller structures. Notably, the second storey consistently recorded the highest interstorey drift ratio, likely due to its exposure to substantial shear forces and diminished stiffness relative to the ground floor.
- Floor Accelerations: The observed maximum floor accelerations varied according to the height of the buildings. Two-storey structures exhibited increased accelerations during sequences of earthquakes, whereas four- and six-storey buildings typically recorded higher accelerations from individual seismic events. This observation highlights the intricate relationship between building height, the characteristics of seismic occurrences, and the dynamic responses of the structures.

The results outlined in this study contest the dominant beliefs in seismic engineering and highlight the urgent need for advanced methodologies in seismic analysis and design. They stress the significance of accounting for both individual and multiple earthquake events, as well as building-specific height considerations, within the framework of seismic design. However, subsequent research efforts should aim to expand the investigation to encompass a more diverse array of structural forms and seismic conditions.

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References

1. Shanmugam, N.E.; Lakshmi, B. State of the art report on steel-concrete composite columns. *J. Constr. Steel Res.* **2001**, *57*, 1041–1080. [CrossRef]
2. Hatzigeorgiou, G.D.; Beskos, D.E. Minimum cost design of fiber reinforced concrete filled steel tubular columns. *J. Constr. Steel Res.* **2005**, *61*, 167–182. [CrossRef]
3. Skalomenos, K.A.; Hatzigeorgiou, G.D.; Beskos, D.E. Parameter identification of three hysteretic models for the simulation of the response of CFT columns to cyclic loading. *Eng. Struct.* **2014**, *61*, 44–60, ISSN 0141-0296. [CrossRef]
4. Serras, D.N.; Skalomenos, K.A.; Hatzigeorgiou, G.D. A displacement/damage controlled seismic design method for MRFs with concrete-filled steel tubular columns and composite beams. *Soil Dyn. Earthq. Eng.* **2021**, *143*, 106608, ISSN 0267-7261. [CrossRef]
5. Katsimpini, P.S.; Papagiannopoulos, G.A. Effectiveness of the Seesaw System as a Means of Seismic Upgrading in Older, Non-Ductile Reinforced Concrete Buildings. *Vibration* **2023**, *6*, 102–112. [CrossRef]
6. Beskos, D.; Katsimpini, P.; Papagiannopoulos, G.; Karabalis, D.; Hatzigeorgiou, G. Seismic performance and design details of low-rise steel structures equipped with the seesaw system. In Proceedings of the 17th World Conference on Earthquake Engineering (2021), Sendai, Japan, 27 September–2 October 2021.
7. Minasidis, G.; Hatzigeorgiou, G.D.; Beskos, D.E. SSI in steel frames subjected to near-fault earthquakes. *Soil Dyn. Earthq. Eng.* **2014**, *66*, 56–68, ISSN 0267-7261. [CrossRef]
8. Anand, V.; Satish Kumar, S.R. Seismic Soil-structure Interaction: A State-of-the-Art Review. *Structures* **2018**, *16*, 317–326, ISSN 2352-0124. [CrossRef]
9. Mylonakis, G.; Gazetas, G.; Nikolaou, S.; Michaelides, O. The role of soil on the collapse of 18 piers of the Hanshin Expressway in the Kobe earthquake. In Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, 30 January–4 February 2000; p. 1074.
10. Cavalieri, F.; Correia, A.A.; Crowley, H.; Pinho, R. Dynamic soil-structure interaction models for fragility characterisation of buildings with shallow foundations. *Soil Dyn. Earthq. Eng.* **2020**, *132*, 106004, ISSN 0267-7261. [CrossRef]
11. Cavalieri, F.; Correia, A.A.; Crowley, H.; Pinho, R. Seismic fragility analysis of URM buildings founded on piles: Influence of dynamic soil–structure interaction models. *Bull. Earthq. Eng.* **2020**, *18*, 4127–4156, ISSN 0267-7261. [CrossRef]
12. Hatzigeorgiou, G.D.; Liolios, A.A. Nonlinear behaviour of RC frames under repeated strong ground motions. *Soil Dyn. Earthq. Eng.* **2010**, *30*, 1010–1025, ISSN 0267-7261. [CrossRef]
13. Mucciarelli, M.; Bianca, M.; Ditommaso, R.; Gallipoli, M.R.; Masi, A.; Milkereit, C.; Vona, M. Far field damage on RC buildings: The case study of Navelli during the L'Aquila (Italy) seismic sequence, 2009. *Bull. Earthq. Eng.* **2011**, *9*, 263–283. [CrossRef]
14. Ditommaso, R.; Iacovino, C.; Auletta, G.; Parolai, S.; Ponzo, F.C. Damage Detection and Localization on Real Structures Subjected to Strong Motion Earthquakes Using the Curvature Evolution Method: The Navelli (Italy) Case Study. *Appl. Sci.* **2021**, *11*, 6496. [CrossRef]
15. Efraimiadou, S.; Hatzigeorgiou, G.D.; Beskos, D.E. Structural pounding between adjacent buildings subjected to strong ground S.motions. Part II: The effect of multiple earthquakes. *Earthq. Eng. Struct. Dyn.* **2013**, *42*, 1529–1545. [CrossRef]
16. Ruggieri, S.; Vukobratović, V. The influence of torsion on acceleration demands in low-rise RC buildings. *Bull. Earthq. Eng.* **2024**, *22*, 2433–2468. [CrossRef]
17. Ruggieri, S.; Vukobratović, V. Acceleration demands in single-storey RC buildings with flexible diaphragms. *Eng. Struct.* **2023**, *275*, 115276, ISSN 0141-0296. [CrossRef]
18. Katsimpini, P.S. Seismic Response of Vertical Hybrid Concrete/Steel Frames Considering Soil–Structure Interaction. *Buildings* **2024**, *14*, 972. [CrossRef]
19. *EN 1993-1*; Eurocode 3: Design of Steel Structures-Part 1.1: General Rules and Rules for Buildings. CEN: Brussels, Belgium, 2009.
20. *EN 1998-1*; Eurocode 4: Design of Structures for Earthquake Resistance. Part 1: General Rules, Seismic Actions and Rules for Buildings. CEN: Brussels, Belgium, 2004.

21. *EC 8*; Eurocode 8—Design of Structures for Earthquake Resistance, Part 1-1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization (CEN): Brussels, Belgium, 2005.
22. *SAP 2000*; Static and Dynamic Finite Element Analysis of Structures: Version 25.0. Computers and Structures: Berkeley, CA, USA, 2023.
23. Serras, D.N.; Skalomenos, K.; Hatzigeorgiou, G.D.; Beskos, D.E. Modeling of circular concrete-filled steel tubes subjected to cyclic lateral loading. *Structures* **2016**, *8*, 75–93. [CrossRef]
24. Kamaris, G.S.; Hatzigeorgiou, G.D.; Beskos, D.E. A new damage index for plane steel frames exhibiting strength and stiffness degradation under seismic motion. *Eng. Struct.* **2013**, *46*, 727–736. [CrossRef]
25. Pacific Earthquake Engineering Research Center. PEER Strong Motion Database. Available online: http://peer.berkeley.edu/smcatS (accessed on 15 July 2009).
26. Mulliken, J.S.; Karabalis, D.L. Discrete model for dynamic through-the-soil coupling of 3-d foundations and structures. *Earthq. Eng. Struct. Dyn.* **1998**, *27*, 687–710. [CrossRef]
27. Cataldo, A.; Roselli, I.; Fioriti, V.; Saitta, F.; Colucci, A.; Tatì, A.; Ponzo, F.C.; Ditommaso, R.; Mennuti, C.; Marzani, A. Advanced Video-Based Processing for Low-Cost Damage Assessment of Buildings under Seismic Loading in Shaking Table Tests. *Sensors* **2023**, *23*, 5303. [CrossRef] [PubMed]
28. Ditommaso, R.; Ponzo, F.C. Automatic evaluation of the fundamental frequency variations and related damping factor of reinforced concrete framed structures using the Short Time Impulse Response Function (STIRF). *Eng. Struct.* **2015**, *82*, 104–112, ISSN 0141-0296. [CrossRef]
29. Puglia, R.; Ditommaso, R.; Pacor, F.; Mucciarelli, M.; Luzi, L.; Bianca, M. Frequency variation in site response as observed from strong motion data of the L'Aquila (2009) seismic sequence. *Bull. Earthq. Eng.* **2011**, *9*, 869–892. [CrossRef]
30. Ditommaso, R.; Ponzo, F.C.; Auletta, G. Damage detection on framed structures: Modal curvature evaluation using Stockwell Transform under seismic excitation. *Earthq. Eng. Eng. Vib.* **2015**, *14*, 265–274. [CrossRef]
31. Sozen, M.A. Review of Earthquake response of reinforced concrete buildings with a view to drift control. In *State-of-the-Art in Earthquake Engineering*; Turkish National Committee on Earthquake Engineering: Istanbul, Turkey, 1981; pp. 383–418.
32. Rodriguez, M.E.; Restrepo, J.I.; Carr, A.J. Earthquake-induced floor horizontal accelerations in buildings. In *Earthquake Engineering & Structural Dynamics: Volume 31 (2002), Special Topics Issue on Performance-Based Earthquake Engineering*; Wiley: Hoboken, NJ, USA, 2002; Issue 3. [CrossRef]
33. Chopra, A. *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, 3rd ed.; Prentice Hall Inc.: Englewood Cliffs, NJ, USA, 2006.
34. Newmark, N.M.; Rosenblueth, E. *Fundamentals of Earthquake Engineering*; Prentice-Hall: Englewood Cliffs, NJ, USA, 1971.