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Seismic Performance of Reinforced Concrete Structures with Concrete Deficiency Caused by In-situ Quality Management Issues

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Abstract

Concrete is a widely used building material known for its cost-effectiveness and high resistance compared to alternative materials. However, uncertainties in the casting process due to variations in the environment and human error can compromise its strength, increasing the risk of collapse when subjected to seismic excitations. Previous studies have demonstrated the detrimental effects of earthquake vibrations on buildings and infrastructure. This study aims to fill the research gap by investigating the seismic behavior of reinforced concrete (RC) structures constructed with lower-quality concrete under near-fault pulse-like ground motions. The main objective of this research is to assess the impact of diminished concrete strength on structural rigidity and susceptibility to ground disturbances. Specifically, the study aims to quantify the extent of performance changes in defective structures, particularly those constructed with poor-quality concrete, in response to seismic activities. To achieve this, the research involves developing multiple finite element models and conducting nonlinear analysis to scrutinize their behavior. A key focus of the study is to compare the performance of various RC buildings with concrete defects to that of a benchmark model. This comparative analysis highlights the influence of suboptimal quality control on the nonlinear behavior of RC structures. Furthermore, the study examines the correlation between changes in building response and earthquake characteristics to provide comprehensive insights into the potential risks associated with substandard construction practices. Based on the results of this study, it was found that inadequate quality control of concrete significantly impacts the performance of RC frames subjected to pulse-like ground motions. The decrease in compressive strength of the concrete led to noticeable increases in various structural parameters, including story shear, overturning moments, story displacement, drifts, accelerations, and hysteretic energy. These findings highlight the detrimental effects of compromised concrete quality on the overall structural response.

Keywords: Reinforced Concrete Frames; Nonlinear Time History Analysis; Concrete Compressive Strength.

1. Introduction

Reinforced concrete (RC) stands as an elemental building material for modern civil engineering projects, largely due to its ubiquitous deployment and substantial significance [1, 2]. Its widespread use, however, comes with its own set of challenges, most notably when RC structures encounter high-intensity seismic activities. Such events can provoke severe damage, such as concrete cover deterioration and rebar yielding, thereby threatening the stability of the structures [3, 4]. Historical analyses have unveiled a strong connection between improper management and the unintended catastrophic collapse of structures under the strain of seismic loads [5, 6]. Furthermore, the inescapable variability inherent in concrete's mechanical properties introduces additional risk factors, enhancing the propensity for either total or partial

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collapse of RC frames [7]. Consequently, in an attempt to safeguard RC structures from potential seismic-related failures, numerous studies have been undertaken over the years examining the ramifications of substandard quality control practices on the behavior of RC buildings exposed to shaking intensities [8–10]. Concurrently, a substantial body of literature has delved into exploring retrofitting strategies aimed at amplifying the resilience of these structures [11, 12].

Over the past few decades, there has been a rising interest in the impact of pulse-like ground motion records, specifically those emanating from earthquakes. Such earthquakes exhibit long-period pulses coupled with high peak ground velocities (PGVs) triggered by the propagation of the fault rupture, leading to consequential damages to the surrounding structures [13]. This near-fault phenomenon was first empirically evidenced in the 1952 Kern County (California) earthquake, with subsequent corroborating evidence provided by ground motions recorded during the seismic events of Northridge (1994), Kobe (1995), Turkey (1999), and Chi-Chi (1999) [14]. Given their significant influence on the behavior of structures and infrastructure, these pulse-like earthquakes have drawn significant research attention for their distinctive characteristics and simulation methods [15, 16]. Research work undertaken by Kohrangi et al. [17] shed light on some previously unexplored facets of pulse-like earthquakes and their impact on the nonlinear dynamic behavior of structures, going beyond the conventional study of the acceleration response spectrum's shape. Additionally, there has been strong advocacy for revising the seismic design norms to encapsulate the effects of pulse-like earthquakes [18]. Nevertheless, the literature offers a limited understanding of the behavior of structures constructed with lower-quality concrete under the strain of near-fault pulse-like earthquakes. Several metrics, including peak ground acceleration (PGA), peak ground velocity (PGV), the ratio of PGA and PGV, and predominant period (Tp), have been employed to illustrate the strength of pulse-like earthquakes [19–21]. However, the interplay between these metrics and the quality of concrete remains under-researched, leaving a significant gap in our understanding of how structures respond to seismic disturbances.

On the other hand, extensive work has been done throughout the recent years to investigate the seismic performance of RC structures. For instance, Opabola and Elwood [22] highlighted the susceptibility of RC beams to single-crack plastic hinge behavior under seismic conditions. Ou et al. [23] further discussed how the seismic behavior of RC beam-column joints can change with the use of unstressed steel strands. Meanwhile, Ahiwale et al. [24] studied the impact of different bracing systems on the seismic performance of RC frames. Their findings reveal that the choice of bracing system can greatly influence the resilience of RC structures during seismic events. Likewise, the work of Cook et al. [25] emphasized the importance of accurately benchmarking nonlinear dynamic procedures against empirical damage observations to assess the seismic performance of RC buildings more effectively. Shegay et al. [26] introduced a novel approach to evaluating the seismic residual capacity ratio for RC structures, which could help predict the expected performance under seismic loads. A more data-driven perspective has been presented by Dogan et al. [27], who employed Deep Transfer Learning to detect damages caused by earthquakes and reinforcement corrosion in RC buildings. The effect of sequential excitations on asymmetrical RC low-rise frame structures has been thoroughly investigated by Askouni [28]. This investigation illuminates how sequential seismic events can degrade the integrity of RC structures. Meanwhile, Ferraioli et al. [29] showcased the potential of retrofitting RC buildings with self-centering shape-memory alloy braces to improve their seismic performance. The research by Deng et al. [30] presents a unique perspective, detailing the effect of saline soil corrosion on the hysteretic model of RC bridge piers based on earthquake damage. Murray et al. [31] investigated the seismic safety of informally constructed reinforced concrete houses in Puerto Rico.

Therefore, this study investigates the seismic behavior of RC frames constructed with lower-quality concrete when subjected to pulse-like ground motions. The aim is to elucidate the impact of diminished concrete strength on the rigidity of the structure and its susceptibility to ground disturbances. A primary objective is to quantify the degree of performance change in defective structures, particularly those constructed with poor-quality concrete, in response to seismic activities. To this end, numerous finite element models will be developed and scrutinized using the nonlinear analysis method. The performance of various concrete-defect RC buildings will be contrasted with that of a benchmark model, thereby highlighting the influence of suboptimal quality control on the nonlinear behavior of RC structures. Furthermore, the correlation between alterations in building response and earthquake characteristics will be examined to deliver comprehensive insights into the potential risks associated with substandard construction practices.

2. Research Methodology

Concrete's physical properties depend on its constituent parts and how they are handled after mixing [32, 33]. Therefore, it is essential to comprehend how each component affects the quality of concrete to create it with the necessary attributes [34]. In order to define and ensure that structural concrete meets standards and specifications, quality management and control are crucial components of the construction process [35]. The most common indicator used for concrete-based components is compression strength, which is also the most challenging to measure. Nonetheless, to make the RC construction resistant to ground motions, it is imperative to provide it with adequate strength. Unexpected earthquake destruction of RC structures still occurs despite substantial advancements in seismic design and construction technologies in recent years. This article estimates the RC frame's sensitivity to poor construction quality. The general research methodology that was used in this paper is shown in Figure 1.

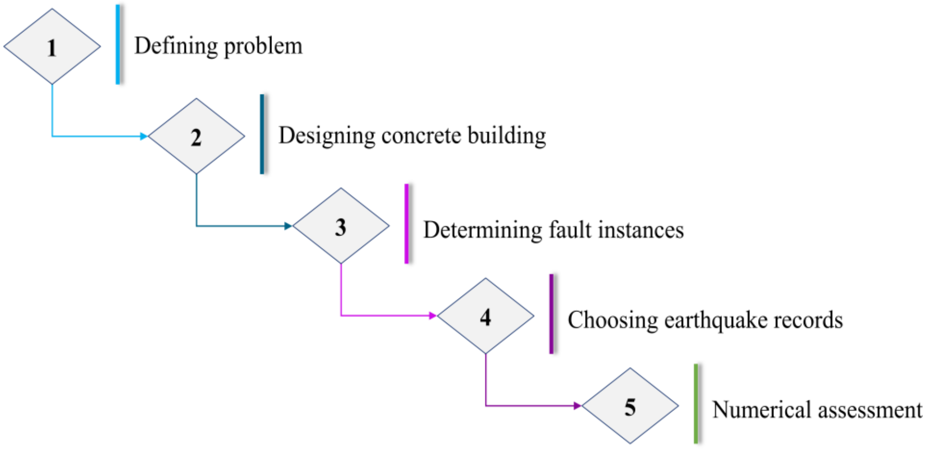


Figure 1. General descriptive illustration of the research methodology

The current study assesses the effect of substandard quality control in concrete casting on the seismic performance of reinforced concrete (RC) buildings. A reference frame was selected to represent low-rise RC buildings, a type commonly found in the Middle East. The case study consisted of three stories and three bays, representing a typical layout in the region. The methodology for developing the scenarios of deficient concrete involved creating three unique concrete batches, each designed to produce a different severity of defect: slight, moderate, or severe. These levels were achieved by changing the compressive strength of the concrete to be 10%, 30%, or 50% less than that of the control concrete. The ACI 318-19 [36] formula was employed to calculate the modulus of elasticity for each batch. Following the creation of these concrete mixes, nine different defective frames were designed. The locations of the concrete strength variations were altered from one story to another, reflecting the reality that in small structures, columns of a single story are typically cast together. Therefore, if the strength of the concrete varies, the entire floor is likely to suffer from the same issue. Figure 3 offers a visual summary of the chosen cases. Each of these frames was represented as a two-dimensional model and evaluated using SAP2000, a recognized finite element software. This study also assumed a location category D, and the MCER response spectrum was established using coefficients SMS = 1.875 g and SM1 = 0.9 g, following the methodology proposed by Ahiwale et al. [24].

The primary compressive strength of the concrete was 30 MPa, while the steel reinforcement used in the experiment had a yielding strength of 420 MPa. To evaluate the impact of cracked sections, a linear elastic method was utilized. This method analyzed the beam and column sections using the effective stiffness characteristics as outlined in ACI 318–19 [36]. The equivalent lateral force method was executed in accordance with the ASCE/SEI 7-22 standard [37] to determine the necessity of retrofitting. A preliminary design was performed using a linear elastic technique to determine the section reinforcement dimensions required for all models. The same dimensions were employed for all frames to isolate the effect of concrete strength variation on the results. The columns and beams were designed with dimensions of 50 cm by 25 cm and 50 cm by 50 cm, respectively. Both geometric and material nonlinearity were considered according to the "NIST GCR 17-917-46v3" guidelines for nonlinear structural analysis [38]. Mander et al.'s procedure [39] was used to account for confinement influences and the behavior of concrete in tension. The stress-strain performance of steel reinforcement under symmetric compression and tension sections was characterized using Park and Paulay's method [40]. Following the approach of Kalantari & Roohbakhsh [41], three distinct fiber sections were identified in the beam and column sections: (1) concrete cover or unconfined concrete; (2) concrete core or confined concrete; and (3) steel reinforcements. The fiber hinge approach was then used to simulate the nonlinear behavior of the structural components.

The SAP2000 software was utilized for the nonlinear time history analysis using the direct integration technique and defining Rayleigh damping at a ratio of 2.5% over the primary vibration modes. This study disregarded the soil-structure interaction while taking into account the P-delta effect. Beam-column panel regions were modeled following the NIST GCR 17-917-46v3 standard, with line segments running from the columns and beams toward the joint panel region. Ground motions for nonlinear analysis were selected from the Pacific Earthquake Engineering Research Center (PEER) website, where eleven pulse-like records were identified. The pulse-like nature of these ground motions was evaluated using Baker's pulse indicator [13] and Hu et al.'s peak ground velocity [42]. Figure 4 illustrates an example of the wavelet decomposition process used to identify pulse-like ground motions, while Table 3 provides a summary of the motions' intensity and characteristics. Several methodologies, including the ACT, ASCE, and Mean Square Error (MSE) methods, can be used to scale chosen earthquake records. In this study, the MSE method was used due to its superior performance in matching spectrums compared to other scaling techniques. Using the PEER online tool, the MSE method was applied to scale the chosen earthquake records across intervals from 0 to 2 seconds to cover the effective periods of all investigated cases. The scaling process included calculating a scale factor for each record, which is necessary to minimize the MSE between the chosen ground motions and the target spectra. This procedure ensured the best possible match between the spectra of the scaled records.

3. Results and Discussions

The decrease in the compressive strength of the concrete in the columns prompts a concomitant decline in the stiffness of the RC structure. This decline in stiffness, albeit slight, is significant as it causes an increment in the building's first mode period, as visibly illustrated in Figure 2. This phenomenon can be understood as a shift in the building's natural frequency due to changes in stiffness, which in turn has an impact on its response to seismic activity. Upon exploring the effects of a reduced concrete compressive strength on structures subjected to pulse-like ground motions, it becomes evident that this reduction leads to an altered shear force. This factor is critical in determining the stability of structures during seismic activity. The shear forces of the benchmark and defect frames were thus evaluated to provide a more detailed understanding of the impact of this drop in compressive strength. The outcomes of the nonlinear response history analysis are juxtaposed in Figure 3, offering a comprehensive comparative analysis. The analysis revealed that a distortion in the concrete's compressive strength, even if only slight, has the potential to alter the average shear force. This could potentially influence the structure's stability during seismic activity. Importantly, our results indicate that the best performance was most consistently observed in the control frame, in contrast to the S1-D50 case, which consistently showed the poorest performance.

Upon evaluating the effects of damage location against one another, the most challenging scenarios appear to be those in which the deficit is near the base level. Specifically, the strength reduction on the ground floor appears to have a more detrimental effect compared to that on the second and third floors. This supports the idea that lower floors are more susceptible to loss of strength and stiffness than higher ones. This susceptibility can be explained by the higher shear forces experienced by the lower floors due to the weight of the floors above. Quantitatively, a 10%, 30%, and 50% decrease in the concrete strength of the columns on the first floor corresponded to an average increase in the floor shear of 1%, 4%, and 7%, respectively. Interestingly, when this strength deficit was shifted to the higher floors, the impact on the shear forces was significantly lower. This reduction was found to be around 0.03%, 1%, and 2% when the deficit occurred for the same level of strength decrease in the story. In the case of the third floor, a similar decline was noted, further emphasizing the relative vulnerability of lower floors to strength and stiffness reduction.

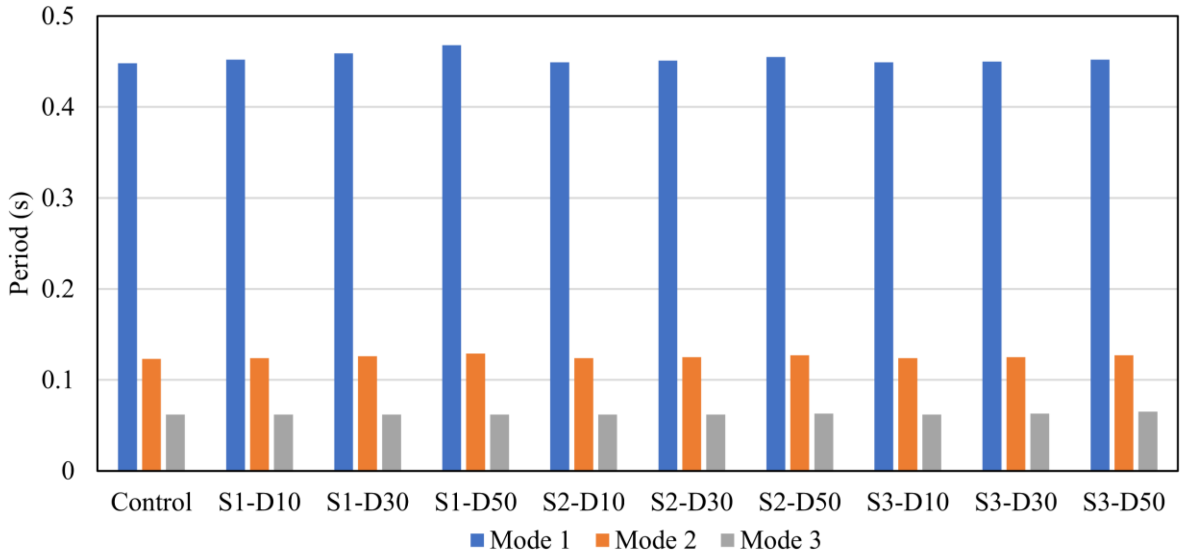


Figure 2. Period of the investigated buildings

Figure 4 provides a graphical representation of the average overturning moment across various frames. A common inference drawn from this figure is that an observable increase in seismic stress on moment-resisting frames is associated with a decrease in the strength and stiffness of the RC frames. Importantly, the upper-story shear pressures and overturning moments can be used as indicators of this correlation and serve as effective measures of the frame's seismic response. Furthermore, the analysis outcomes suggest that a reduction in the compressive strength of the building material subtly but notably influences the behavior of the RC frame. While this influence may seem marginal at first glance, a closer examination of the results reveals a corresponding rise in the overturning moment with this decrease in compressive strength. This finding suggests a heightened risk of structural instability and correlates closely with the high shear discussed previously. The pattern observed in the overturning moment parallels that found in the floor shear results, strengthening the understanding of the effects of compressive strength reduction. Practically speaking, an increase in the overturning moment in a building could result in tilting or even a collapse during significant seismic activity, posing a significant risk to structural safety. The comprehensive findings of the study indicate that the compressive strength of construction material is an integral factor influencing the stability of an RC frame. A reduction in compressive strength doesn't merely impact the frame's rigidity, but it also potentially increases the overturning moment and floor shear forces, thereby escalating seismic vulnerability. Therefore, it can be inferred that ensuring optimal compressive strength of the construction materials during the construction phase can be instrumental in enhancing the frame's resistance to seismic stress.

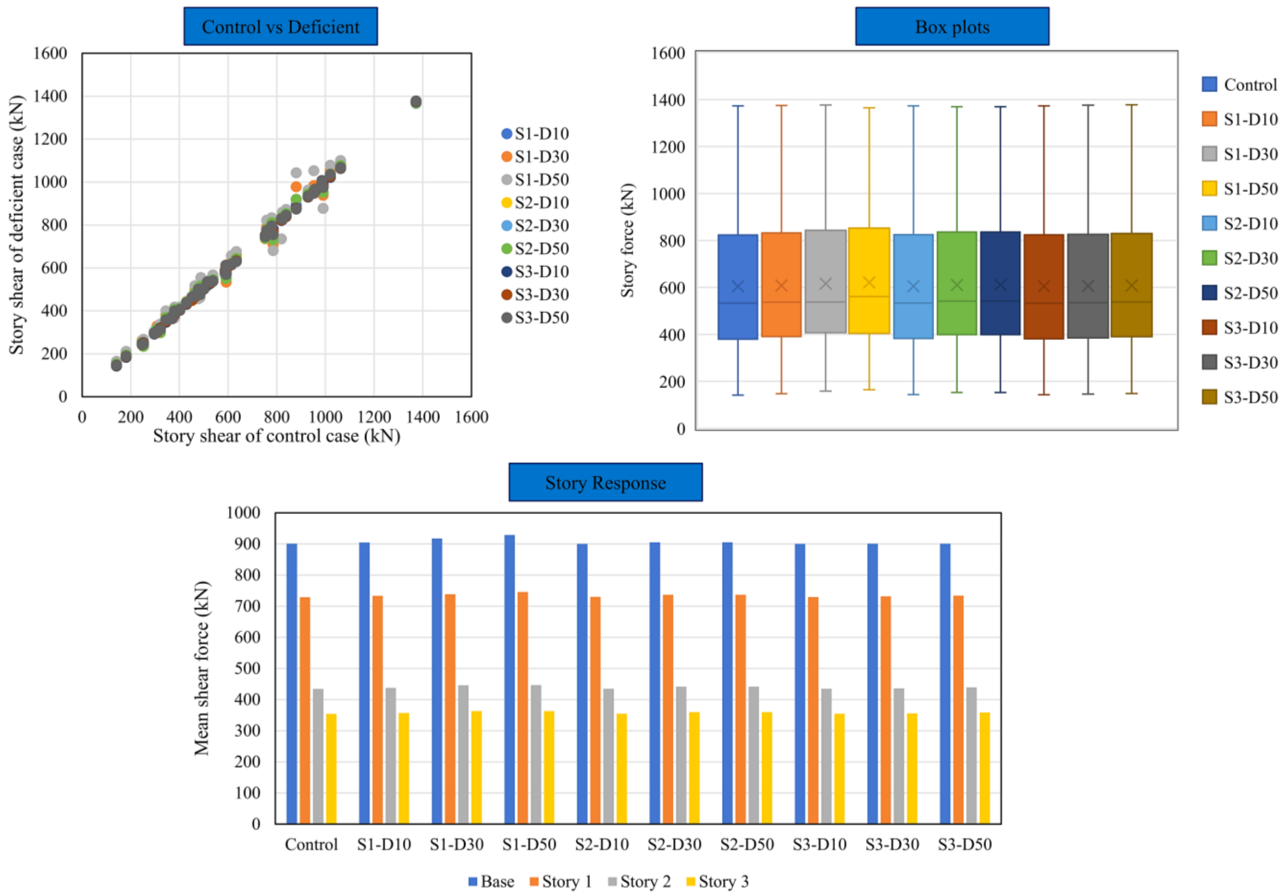


Figure 3. Story shear response of the investigated structures

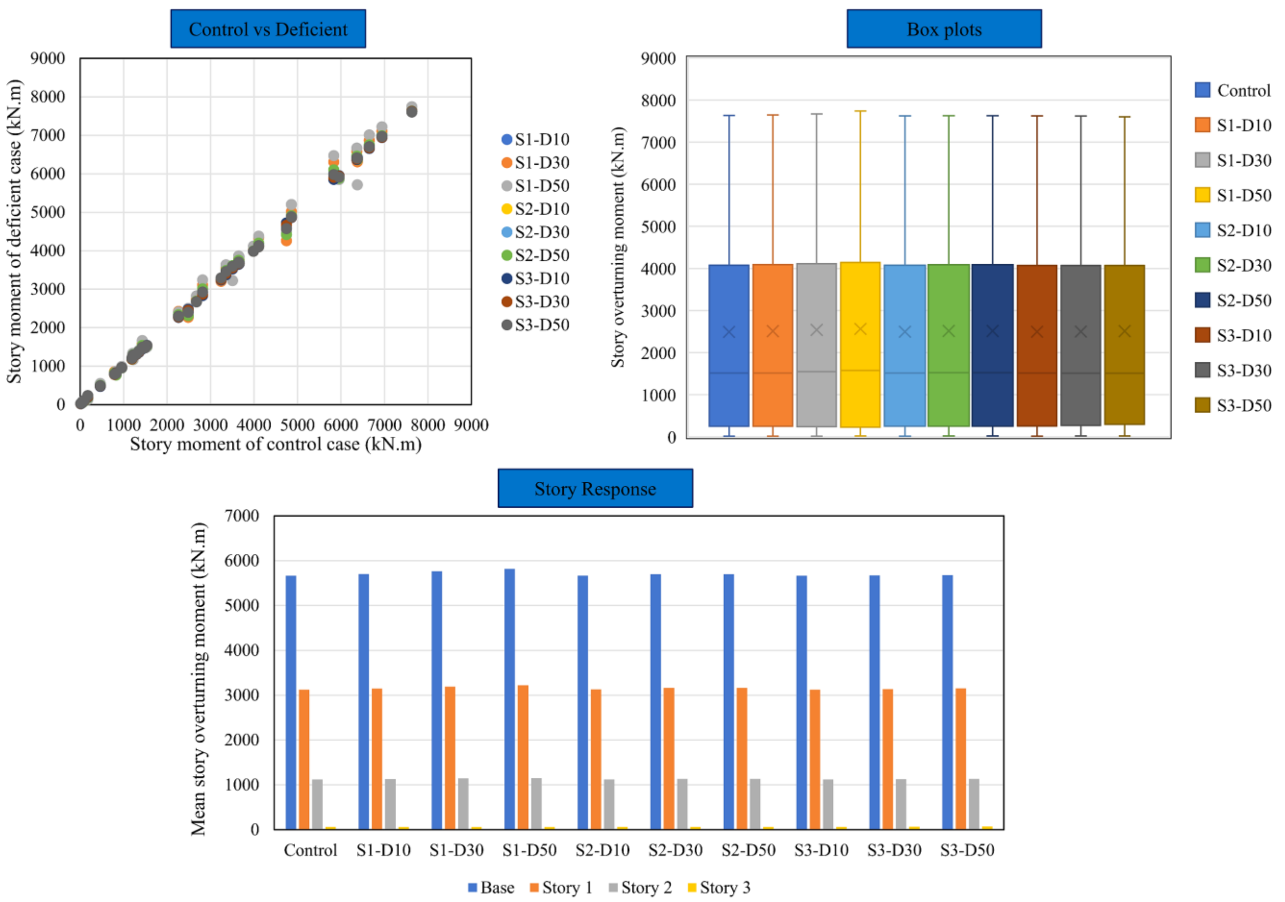


Figure 4. Overturning moment response of the investigated structures

The objective of this section is to scrutinize and assess the displacement behavior of the floors in the structures under study. The outcomes of this analysis are graphically illustrated in Figure 5. A key observation drawn from these outcomes is the pronounced change in floor displacement for the S1-D10, S1-D30, and S1-D50 scenarios compared to other test conditions. This observable change resonates with previous findings, confirming the validity of the identified trends and patterns. The more significant displacement in these scenarios could be attributed to the lower displacement experienced by the second and third floors when juxtaposed against the reference case. This suggests that the concrete quality control on these lower floors might have been less than optimal, which has culminated in a decrease in stiffness.

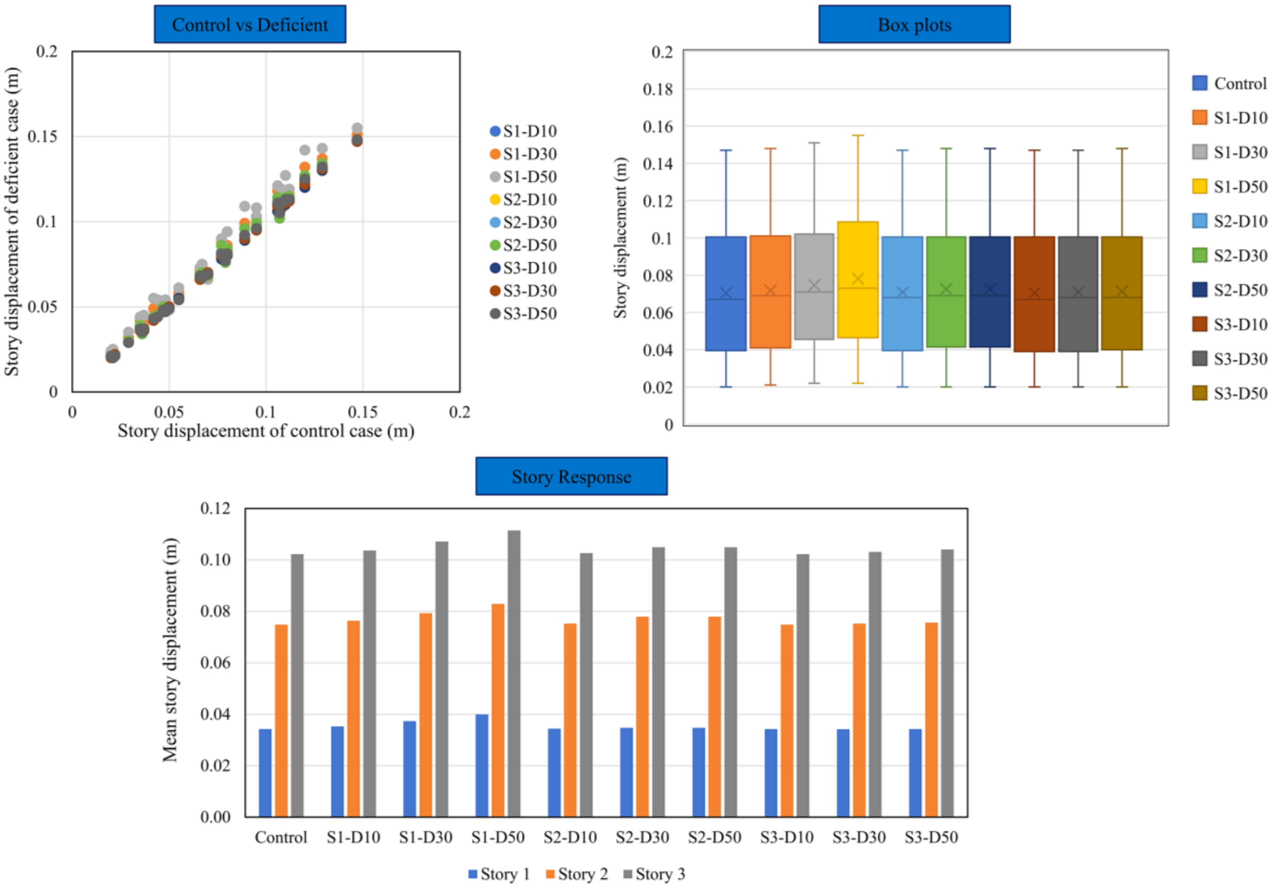


Figure 5. Story displacement response of the investigated structures

Hence, the stiffness of the floors, particularly on the lower levels, is significantly influenced by the quality of the concrete. This points to the criticality of employing high-quality concrete across all building floors to sustain structural integrity in the face of seismic events. In the context of the S1-D50 case, it was identified that this case experienced the steepest decrease in both the mean and envelopment displacements, approximately around 10%. Drawing on these results, it can be inferred that among the scenarios under consideration, the S1-D50 case exhibited the most critical deficiency. This was followed by the S1-D30 and S1-D10 cases in terms of the severity of the observed deficiency. Interestingly, while other models, like the S2-D50 and S3-D50, also registered significant strength reductions, the damage location seemed to ameliorate the overall structural impact, underscoring the importance of damage location in the mitigation of seismic risks. The concept of the inter-story drift ratio emerges as an essential metric for designing reinforced concrete frames capable of withstanding earthquakes. In this study, a nonlinear analysis approach was deployed to determine the inter-story drift ratio, with the findings showcased in Figure 6. These findings reveal that the average drifts saw an uptick for the control case in specific earthquake scenarios.

Moreover, the seismic demand for several instances was found to be higher than for the control building, pointing to the seismic vulnerability of the structures under study. For cases where the third floor was weaker, the drifts closely mirrored the benchmark scenario, suggesting that the floor's strength could potentially influence the drift behavior. In order to evaluate the performance of the buildings, the Hazus standard was utilized. The drift ratios of 0.5%, 1%, 3%, and 8% were classified as representing minor, moderate, extensive, and complete collapse, respectively, according to this standard. Generally, the buildings under study displayed minor to moderate degrees of drift for the chosen earthquake scenarios. However, certain specific scenarios registered a shift from minor to moderate degrees of drift, highlighting the variability in seismic response under different conditions.

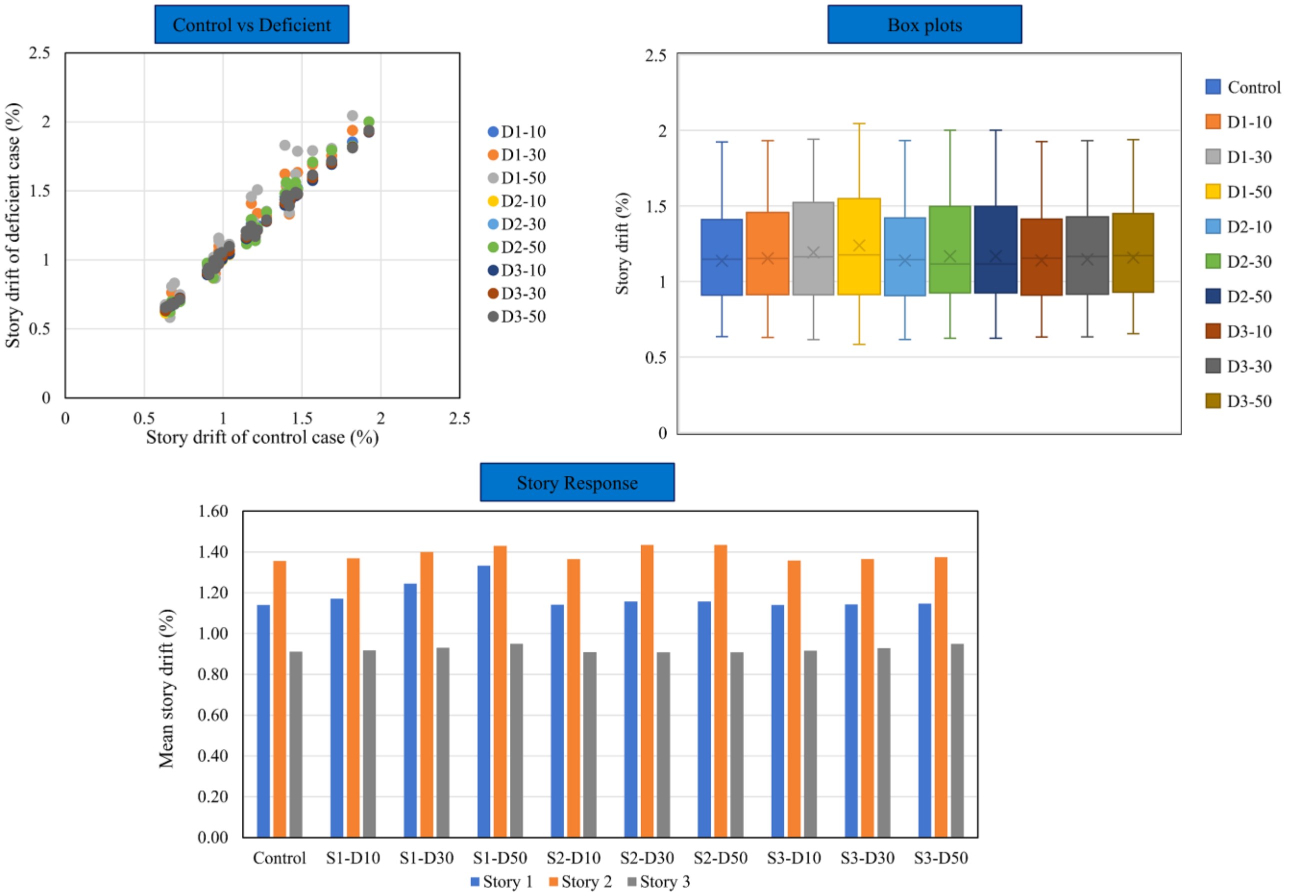


Figure 6. Interstory drift ratio of the investigated structures

The research endeavored to explore the potential impacts of a reduction in the compressive strength of concrete on the floor accelerations of structures when exposed to pulse-like ground disturbances, specifically earthquakes. The pulse-like nature of earthquakes, involving sudden shifts in ground acceleration, provides a valuable and challenging test environment for the integrity and resilience of a structure's design and materials. This in-depth investigation involved examining both the mean responses and the individual records. A central finding from this examination was that a decrease in the concrete's compressive strength resulted in a slight yet noteworthy increase in the building's acceleration. This outcome underscores the importance of concrete strength as a critical factor in managing a structure's response to seismic activity, demonstrating the crucial role of concrete's compressive strength in moderating structural accelerations and, by extension, the overall stability of a building during an earthquake. In terms of individual building performance, the structure that experienced the most significant decrease in strength (S1-D50) also demonstrated the poorest performance.

This aligns with the expectation that strength loss in concrete could compromise a structure's ability to withstand seismic stress, emphasizing the importance of maintaining optimal compressive strength to ensure seismic resilience. A story-by-story analysis of the results further corroborated these findings, adding additional depth and context to our understanding of the role of concrete's compressive strength. This nuanced perspective offers insights into how strength reductions can differentially impact various levels of a building, underscoring the importance of maintaining high-quality construction materials throughout the structure. These findings offer substantial evidence to confirm and extend the conclusions drawn from earlier studies. They underline the essential role of concrete's compressive strength in managing a building's response to pulse-like ground motions, thereby enhancing our understanding of how best to design and construct structures for improved seismic resistance. Finally, the results of this comprehensive analysis are visually presented in Figure 7. This illustration serves as a succinct summary of the findings, providing a clear and easy-to-understand representation of how reductions in compressive strength can influence structural accelerations.

Figure 8 provides a graphical depiction of various energy parameters in the examined structures, including average input, potential, kinetic, damping, and hysteretic energies. An increase in these energies is generally observed with a higher percentage of compressive strength reduction. Furthermore, when the defect is located lower in the structure, a decrease in the overall strength of the material is noted. These observations suggest a relationship between energy behavior, the strength of the material, and the location of defects, underlining the intricate interactions of these elements in the structure's response to seismic forces. The data indicates that the mean energy contributed by the frames with deficiencies on the third floor is the least among all the tested structures. This could be a manifestation of the structure's compensatory mechanisms working to offset the effects of deficiencies on higher floors, or it might highlight the effect of load distribution across the structure's height. Regardless, it accentuates the role of the vertical location of defects in the overall energy behavior of a structure. However, when the maximum response is considered, as portrayed in Figure 9, only a minor variation is detected. This suggests that while the average energy behavior can vary significantly depending on the strength of the material and the defect's location, the maximum energy response tends to be more consistent across different conditions. This could imply inherent resistance mechanisms within the structures that limit peak energy response, irrespective of the degree of strength loss or defect location (Figure 10). Among the tested scenarios, the S1-D50 case is identified as the worst-case scenario, exhibiting the most significant adverse effects due to strength reduction. Conversely, the S3-D10 case emerges as the best case, demonstrating the least structural impact due to the defect. Interestingly, both of these cases are close to the control model, implying that the structural impact of defects might not always correlate directly with the extent of strength reduction or the defect's position.

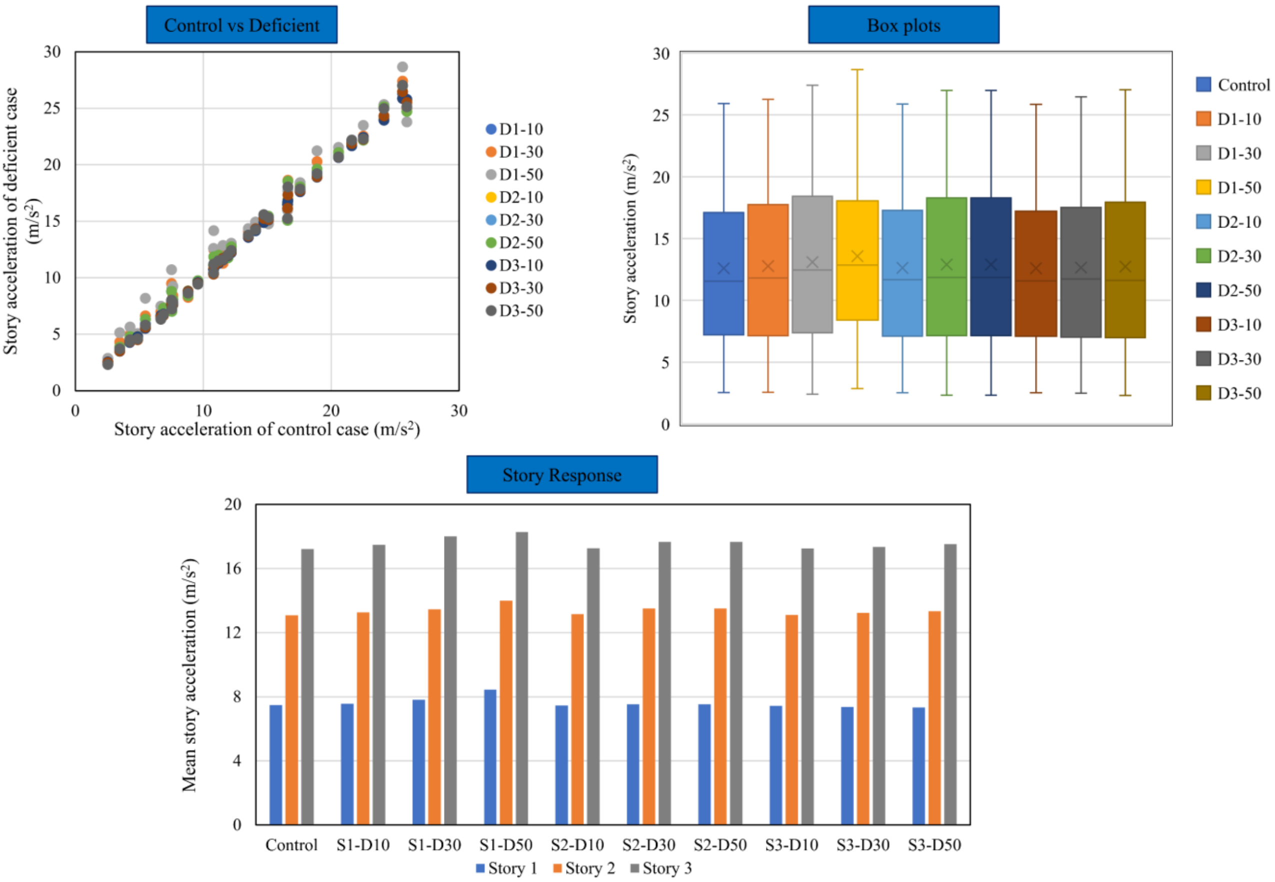
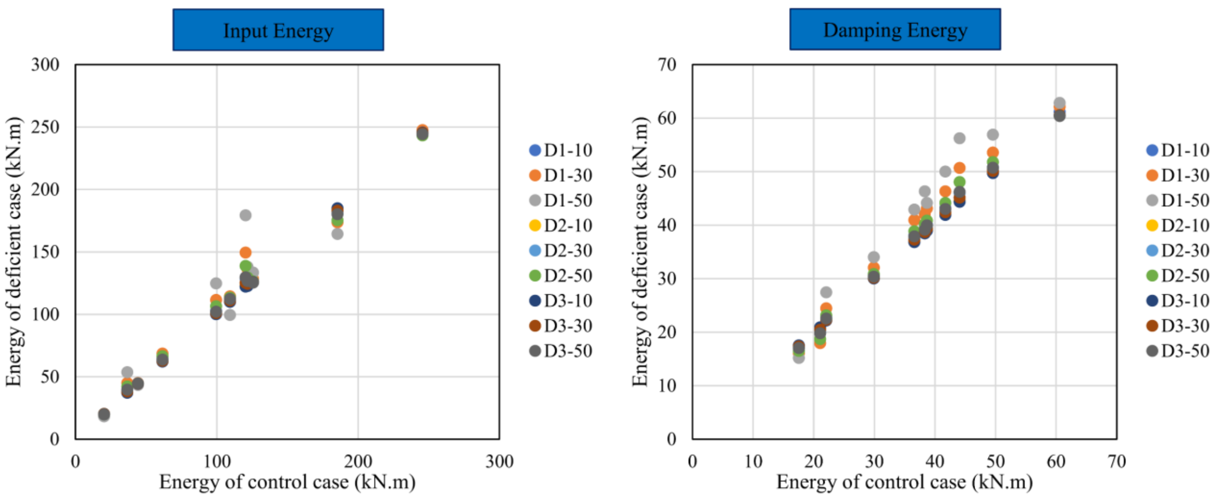


Figure 7. Story acceleration of the investigated structures



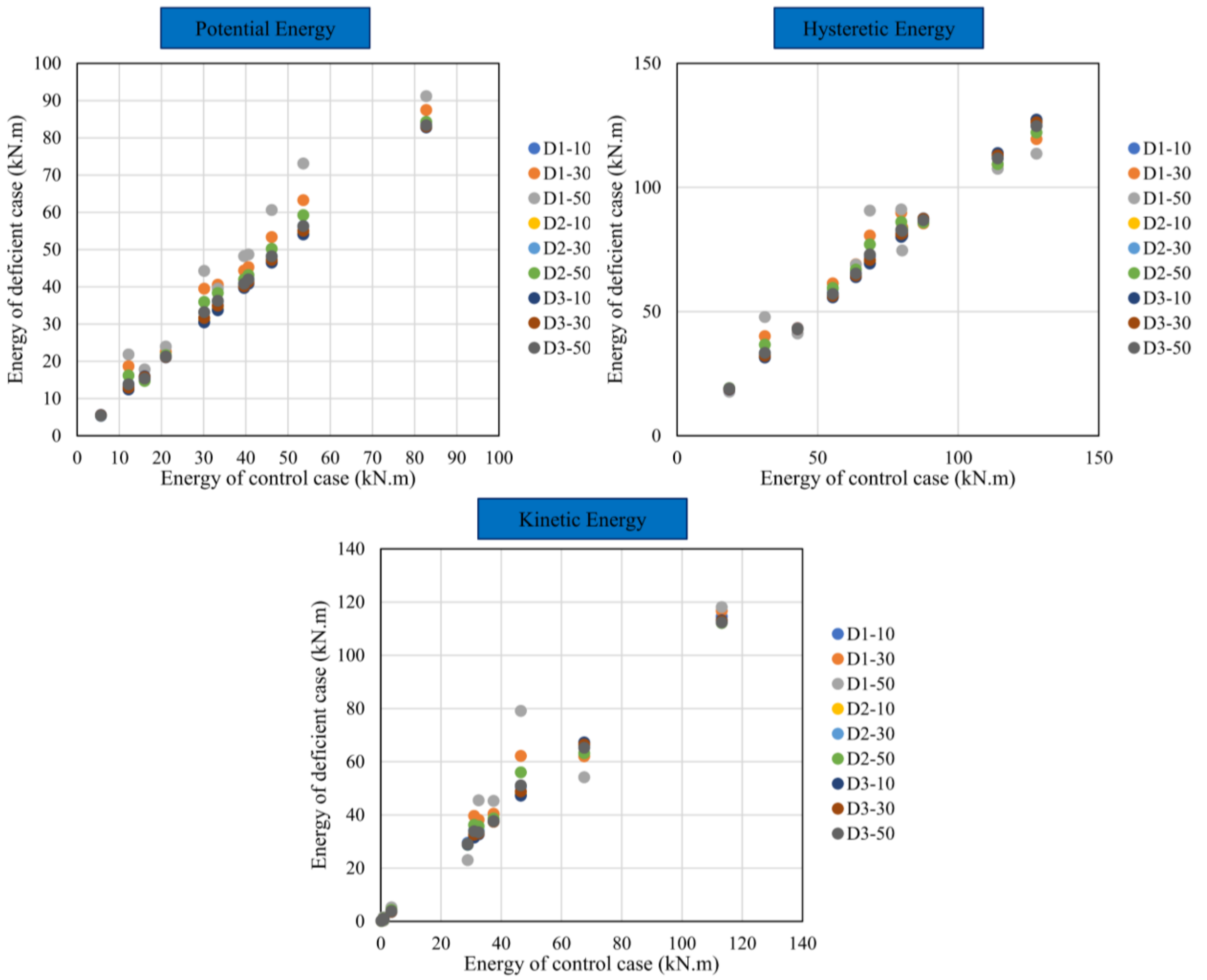
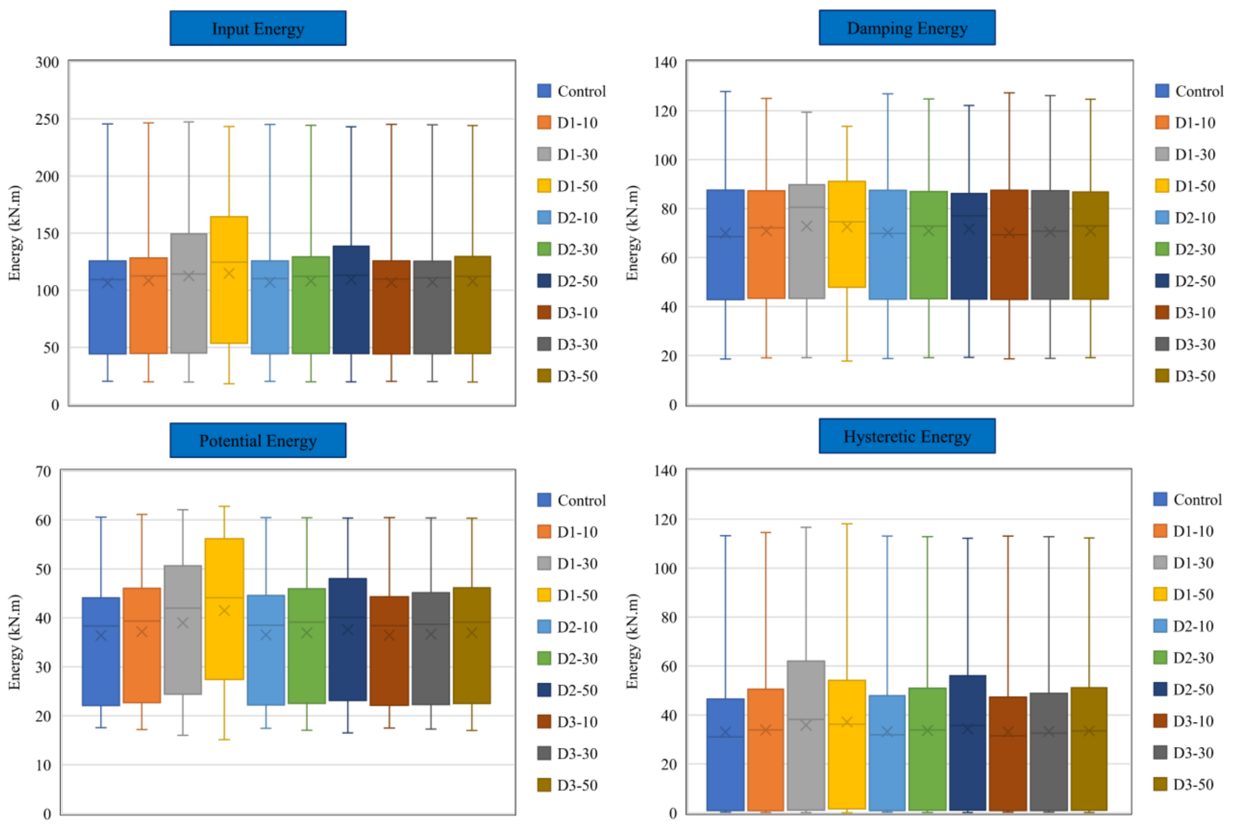


Figure 8. Energy components of the control building versus the deficient ones



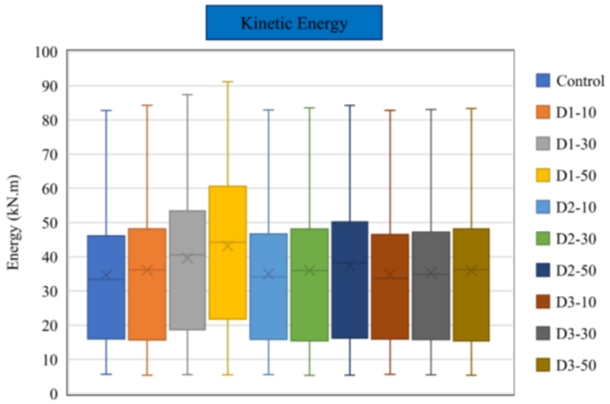


Figure 9. Box plot of the energy components in the investigated structures

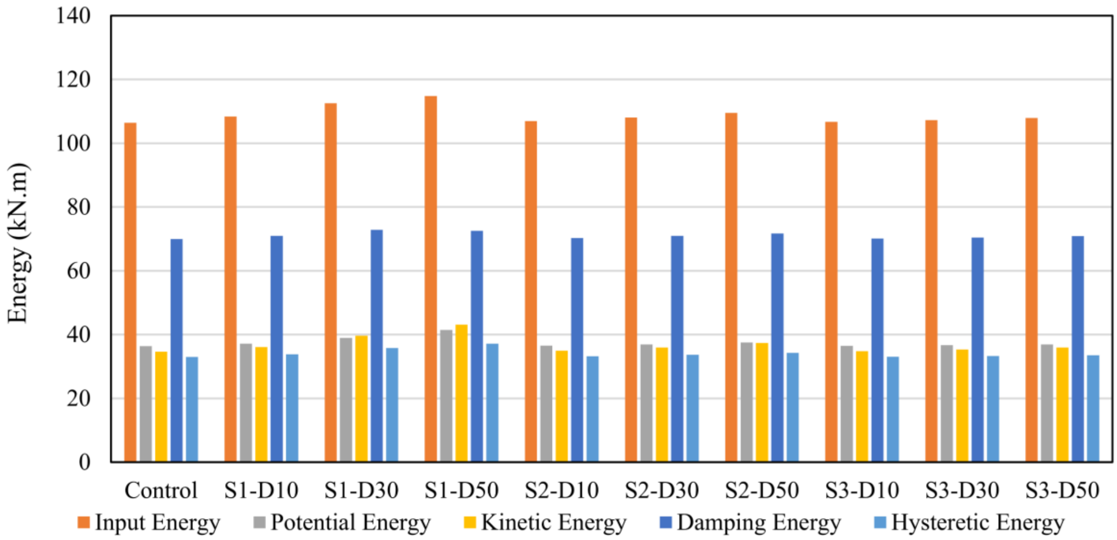


Figure 10. Mean of the peak energy components in the investigated structures

The aim of this research was to assess the ramifications of reductions in concrete's compressive strength and the location of these reductions on the behavior and response of RC frames. It offers valuable insights into the relationship between the compressive strength of the concrete, its location within the frame, and the overall performance of the structure. The data strongly indicates that among the different scenarios, the S1-D50 case had the most pronounced impact on various measures, such as story shear and displacements, with a maximum influence of approximately 20%. The S1-D30 case had a marginally lesser impact, while the S1-D10 scenario exhibited a significantly greater impact than the S2-D10 and S3-D10 cases, despite experiencing an identical degree of strength reduction. This suggests the location of the deficiency to be a substantial factor influencing these differences, which underscores the criticality of not just the strength of the concrete but also the distribution of this strength within the structure. In terms of the overturning moment, the S1-D50 and S3-D50 scenarios revealed discernible discrepancies.

Specifically, the S1-D50 case demonstrated consistently positive peaks, while the S3-D50 scenario displayed high negative peaks. A few data points in the S3-D50 case stood out as anomalies, necessitating further investigation. Overall, these findings accentuate the importance of considering both the degree of strength reduction and the location of the deficiency when evaluating the impact on a variety of structural metrics. The second facet of this study focused on examining the correlation between the response of structures (such as the changes in shear and overturning moment) and a variety of earthquake characteristics, including peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), the ratio of PGA to PGV, arias intensity (Tp), shear wave velocity of the soil (Vs30), and distance to the rupture plane. The results depicted in Figures 11 and 12 reveal that the shear change was most significantly influenced by Vs30, with Tp and PGD also contributing to the observed variations. The research shows that the distance to the rupture plane had the least bearing on the shear response. Interestingly, arias intensity had the lowest correlation coefficient for the overturning moment, although the distance to the rupture plane was not the least influential factor.

Story Shear

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.17	-0.02	0.32	-0.27	-0.22	0.38	0.04	-0.26
S1-D10	0.17	-0.04	0.32	-0.28	-0.23	0.38	0.05	-0.27
S1-D30	0.18	-0.07	0.31	-0.30	-0.25	0.37	0.04	-0.27
S1-D50	0.18	-0.05	0.31	-0.31	-0.23	0.38	0.03	-0.25
S2-D10	0.17	-0.03	0.32	-0.28	-0.23	0.38	0.04	-0.26
S2-D30	0.18	-0.06	0.32	-0.29	-0.25	0.39	0.04	-0.28
S2-D50	0.18	-0.06	0.32	-0.29	-0.25	0.39	0.04	-0.28
S3-D10	0.17	-0.02	0.32	-0.28	-0.22	0.38	0.04	-0.26
S3-D30	0.18	-0.03	0.32	-0.28	-0.23	0.39	0.05	-0.27
S3-D50	0.18	-0.04	0.32	-0.29	-0.24	0.39	0.05	-0.28

Story Overturning Moment

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.08	-0.01	0.15	-0.12	-0.10	0.16	0.03	-0.12
S1-D10	0.08	-0.02	0.14	-0.12	-0.11	0.16	0.03	-0.12
S1-D30	0.08	-0.04	0.14	-0.13	-0.12	0.15	0.03	-0.13
S1-D50	0.09	-0.03	0.13	-0.14	-0.11	0.16	0.03	-0.11
S2-D10	0.08	-0.01	0.15	-0.12	-0.10	0.16	0.03	-0.12
S2-D30	0.08	-0.02	0.14	-0.13	-0.12	0.16	0.03	-0.13
S2-D50	0.08	-0.02	0.14	-0.13	-0.12	0.16	0.03	-0.13
S3-D10	0.08	-0.01	0.15	-0.12	-0.10	0.16	0.03	-0.12
S3-D30	0.08	-0.01	0.14	-0.12	-0.11	0.16	0.03	-0.12
S3-D50	0.08	-0.01	0.14	-0.13	-0.11	0.16	0.03	-0.12

Story Displacement

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.10	-0.08	0.28	-0.34	-0.30	0.39	-0.03	-0.32
S1-D10	0.09	-0.07	0.29	-0.32	-0.30	0.38	-0.02	-0.32
S1-D30	0.07	-0.05	0.31	-0.28	-0.28	0.37	0.02	-0.31
S1-D50	0.07	-0.04	0.36	-0.28	-0.30	0.39	0.06	-0.33
S2-D10	0.10	-0.08	0.28	-0.33	-0.30	0.39	-0.03	-0.32
S2-D30	0.08	-0.06	0.30	-0.29	-0.28	0.37	0.00	-0.30
S2-D50	0.08	-0.06	0.30	-0.29	-0.28	0.37	0.00	-0.30
S3-D10	0.10	-0.08	0.28	-0.33	-0.30	0.39	-0.03	-0.32
S3-D30	0.09	-0.08	0.28	-0.32	-0.30	0.38	-0.02	-0.32
S3-D50	0.08	-0.07	0.28	-0.31	-0.28	0.38	-0.01	-0.31

Interstory Drift

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.15	-0.11	0.42	-0.51	-0.46	0.58	-0.05	-0.49
S1-D10	0.12	-0.10	0.43	-0.48	-0.44	0.57	-0.03	-0.47
S1-D30	0.09	-0.07	0.45	-0.42	-0.40	0.53	0.02	-0.44
S1-D50	0.08	-0.04	0.49	-0.40	-0.40	0.53	0.07	-0.44
S2-D10	0.14	-0.11	0.42	-0.50	-0.46	0.57	-0.05	-0.48
S2-D30	0.10	-0.07	0.42	-0.42	-0.40	0.52	0.00	-0.43
S2-D50	0.10	-0.07	0.42	-0.42	-0.40	0.52	0.00	-0.43
S3-D10	0.14	-0.11	0.42	-0.51	-0.46	0.58	-0.05	-0.49
S3-D30	0.13	-0.11	0.43	-0.50	-0.46	0.58	-0.04	-0.49
S3-D50	0.12	-0.09	0.44	-0.48	-0.45	0.57	-0.03	-0.48

Story Acceleration

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.27	0.03	0.54	-0.48	-0.38	0.63	-0.02	-0.41
S1-D10	0.25	0.03	0.53	-0.47	-0.37	0.62	-0.02	-0.41
S1-D30	0.23	0.05	0.50	-0.46	-0.33	0.61	-0.03	-0.38
S1-D50	0.20	0.09	0.49	-0.46	-0.29	0.62	-0.06	-0.34
S2-D10	0.26	0.04	0.53	-0.48	-0.37	0.63	-0.02	-0.41
S2-D30	0.23	0.05	0.51	-0.46	-0.35	0.61	-0.02	-0.39
S2-D50	0.23	0.05	0.51	-0.46	-0.35	0.61	-0.02	-0.39
S3-D10	0.27	0.04	0.53	-0.48	-0.37	0.63	-0.02	-0.41
S3-D30	0.26	0.03	0.52	-0.47	-0.37	0.63	-0.02	-0.41
S3-D50	0.24	0.03	0.52	-0.47	-0.36	0.62	-0.02	-0.40

Figure 11. Pearson's correlation coefficients for the influence of earthquake properties on the response of the investigated buildings

Input Energy

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.20	-0.20	0.31	-0.60	-0.39	0.70	-0.11	-0.45
S1-D10	0.20	-0.18	0.33	-0.59	-0.39	0.70	-0.11	-0.45
S1-D30	0.22	-0.12	0.39	-0.58	-0.39	0.72	-0.11	-0.46
S1-D50	0.27	-0.03	0.48	-0.58	-0.45	0.74	-0.09	-0.54
S2-D10	0.20	-0.19	0.32	-0.59	-0.39	0.70	-0.11	-0.45
S2-D30	0.20	-0.17	0.33	-0.59	-0.39	0.71	-0.11	-0.45
S2-D50	0.21	-0.14	0.36	-0.58	-0.39	0.71	-0.11	-0.45
S3-D10	0.20	-0.20	0.32	-0.60	-0.39	0.70	-0.11	-0.45
S3-D30	0.20	-0.19	0.32	-0.59	-0.39	0.70	-0.11	-0.45
S3-D50	0.21	-0.18	0.33	-0.59	-0.39	0.70	-0.11	-0.45

Damping Energy

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.25	-0.14	0.53	-0.62	-0.54	0.74	-0.04	-0.59
S1-D10	0.24	-0.16	0.52	-0.61	-0.56	0.72	-0.02	-0.60
S1-D30	0.23	-0.19	0.52	-0.60	-0.59	0.68	0.03	-0.62
S1-D50	0.21	-0.16	0.55	-0.59	-0.57	0.66	0.10	-0.61
S2-D10	0.24	-0.14	0.53	-0.62	-0.55	0.73	-0.03	-0.59
S2-D30	0.24	-0.16	0.53	-0.61	-0.56	0.72	-0.02	-0.60
S2-D50	0.24	-0.17	0.53	-0.61	-0.57	0.70	0.01	-0.62
S3-D10	0.24	-0.14	0.53	-0.62	-0.54	0.74	-0.04	-0.59
S3-D30	0.24	-0.15	0.52	-0.61	-0.55	0.73	-0.03	-0.60
S3-D50	0.24	-0.16	0.52	-0.61	-0.56	0.71	-0.01	-0.60

Potential Energy

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.19	-0.03	0.62	-0.70	-0.55	0.91	-0.09	-0.60
S1-D10	0.17	-0.02	0.61	-0.69	-0.53	0.90	-0.10	-0.59
S1-D30	0.14	0.05	0.61	-0.67	-0.48	0.88	-0.10	-0.54
S1-D50	0.14	0.11	0.64	-0.68	-0.47	0.89	-0.10	-0.53
S2-D10	0.19	-0.03	0.62	-0.70	-0.54	0.91	-0.09	-0.60
S2-D30	0.17	-0.01	0.61	-0.69	-0.52	0.90	-0.10	-0.59
S2-D50	0.15	0.03	0.61	-0.68	-0.50	0.89	-0.10	-0.56
S3-D10	0.19	-0.03	0.62	-0.70	-0.54	0.91	-0.09	-0.60
S3-D30	0.18	-0.02	0.61	-0.70	-0.54	0.91	-0.09	-0.60
S3-D50	0.17	-0.01	0.61	-0.69	-0.53	0.90	-0.10	-0.59

Hysteretic Energy

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.11	-0.21	0.24	-0.50	-0.27	0.58	-0.01	-0.33
S1-D10	0.11	-0.19	0.25	-0.49	-0.26	0.57	-0.01	-0.32
S1-D30	0.09	-0.12	0.26	-0.47	-0.25	0.55	-0.04	-0.31
S1-D50	0.12	-0.08	0.29	-0.48	-0.31	0.54	-0.04	-0.39
S2-D10	0.11	-0.21	0.25	-0.50	-0.27	0.58	-0.01	-0.32
S2-D30	0.11	-0.18	0.25	-0.49	-0.26	0.57	-0.02	-0.32
S2-D50	0.10	-0.15	0.26	-0.48	-0.25	0.56	-0.03	-0.31
S3-D10	0.11	-0.21	0.24	-0.50	-0.27	0.58	-0.01	-0.32
S3-D30	0.11	-0.20	0.25	-0.49	-0.26	0.57	-0.01	-0.32
S3-D50	0.11	-0.18	0.25	-0.49	-0.26	0.57	-0.02	-0.32

Kinetic Energy

Correlation Matrix								
Case	Rrup	Vs30	PGA	PGV	PGD	PGA/PGV	Arias	Tp
Control	0.28	-0.22	0.37	-0.69	-0.49	0.80	-0.18	-0.55
S1-D10	0.29	-0.20	0.39	-0.68	-0.50	0.80	-0.18	-0.56
S1-D30	0.32	-0.15	0.46	-0.66	-0.52	0.81	-0.16	-0.59
S1-D50	0.38	-0.05	0.57	-0.64	-0.55	0.83	-0.11	-0.63
S2-D10	0.28	-0.21	0.38	-0.69	-0.50	0.80	-0.18	-0.55
S2-D30	0.29	-0.20	0.40	-0.68	-0.50	0.80	-0.18	-0.56
S2-D50	0.31	-0.17	0.43	-0.67	-0.52	0.81	-0.17	-0.58
S3-D10	0.28	-0.21	0.38	-0.69	-0.50	0.80	-0.18	-0.55
S3-D30	0.29	-0.21	0.39	-0.69	-0.50	0.80	-0.18	-0.55
S3-D50	0.29	-0.20	0.40	-0.68	-0.50	0.80	-0.18	-0.56

Figure 12. Pearson's correlation coefficients for the earthquake properties impact the energy components of the investigated buildings

There is a correlation between the arias intensity and Rrup with the story displacement, and the floor drift. Furthermore, all three variables (arias intensity, Vs30, and Rrup) are statistically significant in predicting story displacement and drift, as indicated by their fairly high Pearson's correlation coefficients. Multiple intensities, including PGV and PGD, influence floor acceleration. Pearson's correlation coefficient assessment results showed that several parameters affected the change in input energy. The arias intensity had the highest impact, while the Vs30 value also had an influence. Regarding potential energy, the most critical parameter was PGV, but Tp, PGD, arias intensity, and Vs30 also played a role. The Rrup was more significant than the arias intensity in potential energy. The Pearson's correlation coefficient results also indicated that PGV and Vs30 were necessary for the damping energy, while the Tp, PGA, PGV, and PGD ratio of PGA/PGV had a better impact on the hysteretic energy.

4. Conclusion

In conclusion, this study provides valuable insights into the effects of inadequate quality control of concrete on the performance of RC frames subjected to pulse-like ground motions. While previous studies have examined the impact of earthquakes on RC structures, the focus on low-quality concrete and pulse-like ground vibrations sets this research apart. The findings of the study indicate that a decrease in the compressive strength of the concrete leads to increased mean values for various structural parameters. These include story shear, overturning moments, story displacement, drifts, accelerations, and hysteretic energy. The higher mean values observed in concrete with lower strength highlight the adverse consequences of compromised concrete quality on the overall structural response. Interestingly, even when using the same proportion of strength capacity, it was found that the first story was more vulnerable to strength reduction impacts compared to other stories. This vulnerability persisted even when comparing stories with an equal number of floors. These results underscore the criticality of maintaining adequate concrete quality, particularly in the lower stories, to ensure structural integrity and resilience during pulse-like ground motions.

The study further reveals that the response of multi-story frames to pulse-like ground motions is primarily influenced by pulse duration, shear wave velocity, and peak ground density. Understanding the behavior of structures under these specific ground motion characteristics is crucial for designing buildings capable of withstanding such dynamic forces. To expand knowledge in this field, further research is warranted. Future studies should aim to investigate the behavior of concrete mixtures containing recycled aggregates and alternative materials, as well as the impact of strength reduction on different construction types. Such research endeavors will contribute to a comprehensive understanding of the implications of inadequate concrete quality and aid in the development of improved construction practices and guidelines. In summary, this study emphasizes the significance of stringent quality control measures in concrete production and highlights the importance of considering pulse-like ground motions in assessing structural performance. The findings serve as a valuable resource for engineers, designers, and policymakers, offering insights to enhance the resilience of RC frames and improve the overall safety and sustainability of built environments.

5. Declarations

5.1. Author Contributions

Conceptualization, Y.A. and A.A.; methodology, E.A.; formal analysis, A.A. and B.Y.; investigation, Y.A.; writing—original draft preparation, A.A. and Y.A.; writing—review and editing, E.A. and B.Y.; visualization, Y.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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