



Directional displacement demand in tall RC buildings under pulse-like ground motions

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Abstract

Ground motion directionality under pulse-like excitation significantly affects structural demand in tall buildings, but its interaction with lateral force-resisting systems is not fully quantified. This study investigates the orientation-dependent response of a rectangular reinforced concrete building subjected to pulse-like motions from the 2023 Turkey earthquake. Four structural configurations are investigated: a regular moment-resisting frame, a shear wall system, a fluid viscous damper system, and a combined system. Bidirectional ground motions are rotated from 0 to 180 degrees and evaluated using time-history analysis with the Fast Nonlinear Analysis procedure. Since peak responses in orthogonal directions do not occur simultaneously, the governing roof displacement at each orientation is defined as the maximum absolute peak response in the principal directions. Dispersion, normalization, and exceedance-based performance indices are used to quantify directional variability and system effectiveness. The mean DSIE values are 0.212, 0.188, 0.318, and 0.313 for the regular, fluid viscous damper, shear wall, and combined configurations, respectively, with the FVD configuration reducing mean directional dispersion by approximately 11.3% relative to the regular frame. The mean NSER of the FVD configuration is 0.858, indicating an overall reduction in roof displacement, although a maximum NSER of 1.336 occurs for GM 4631 at 6°. The dominant pulse periods exceed the fundamental periods of all configurations, indicating long-period pulse characteristics relative to the structural periods. The findings indicate that orientation-dependent pulse-structure interaction can change the relative effectiveness of the investigated stiffness- and damping-based systems, emphasizing orientation-dependent evaluation in performance-based seismic design.

1. Introduction

Ground motion directionality remains a critical challenge in the seismic assessment of reinforced concrete structures, as orientation-dependent excitation can significantly alter structural demand and safety [1,2]. Ground motion recordings contain two orthogonal horizontal components [3]. The horizontal components often exhibit unequal amplitudes, leading to variances in intensity measures (IM) across different orientations in the horizontal plane, a phenomenon known as GM directionality [4]. The variability complicates seismic hazard assessments and the seismic design of structures, as the directional properties of ground motions can modify the demands on structural components and greatly affect their performance during seismic events [5,6].

Numerous researchers have empirically examined GM directionality utilising recorded strong motion data [4,7–11]. The directionality in the 2010–2011 Canterbury earthquakes in New Zealand was analysed utilising a dataset of ground motions from 20 strong motion stations over 10 seismic events [12]. Their analysis concentrated on response spectral directionality ratios and the alignment of maximum spectral acceleration. The NGA-West2 project significantly improved the understanding of GM directionality. Empirical models have been formulated for direction-dependent spectral characteristics, emphasising the ratio of SaRotD100 (the maximum spectral acceleration over all possible non-redundant rotation angles) to the SaRotD50 (the median spectral acceleration over all possible rotation angles) [13].

These models indicated that SaRotD100 is generally 10-15% greater than SaRotD50, underscoring the need to incorporate directionality in seismic hazard assessment.

A methodology has been proposed in the literature for building structures to ensure safety against single or dual independent orthogonal motions applied horizontally in any direction relative to the structural axis, and it employs time-history analysis to assess structural behaviour and produce fragility curves [14]. The impact of pounding on base-isolated structures has been examined in a study, which demonstrated that unidirectional excitations could underestimate base-drift demands [15]. Their three-dimensional simulations varied parameters such as incidence angle, seismic clearance, and mass eccentricities, demonstrating a substantial impact of GM directionality on the peak inter-story drift ratio. The influence of directional variation of recorded horizontal GM components on the longitudinal reinforcement demands of RC frame members has been investigated using three single-story structures subjected to thirteen recorded bidirectional ground motions. The study demonstrated that reinforcement estimates obtained using multiple design approaches were significantly affected by the orientation of the ground motion recording angle [16]. The combined influence of directionality and pulse duration on the seismic response of high-rise structures has also been examined, with particular emphasis on pulse-like ground motions characterised by intense velocity pulses that are especially critical for long-period structures [17,18]. To address orientation-dependent displacement demand, a method was proposed to determine the critical response of tall structures using the maximum ground motion velocity, providing a computationally efficient alternative to conventional approaches. It was further shown that restricting analysis to fault-normal or fault-parallel orientations may underestimate the true maximum structural response, whereas evaluation across all possible orientations yields a more accurate representation of critical demand [19]. These findings emphasise the need to explicitly account for directionality effects in seismic design, especially for pulse-dominated excitation.

However, without systematically analysing how various lateral force-resisting systems react to directed pulse alignment, most of the recent research mainly concentrates on spectral amplification ratios or peak response envelopes. In tall reinforced concrete buildings, damping-dominated systems like fluid viscous dampers, stiffness-dominated systems like shear walls, or hybrid mixtures of both are frequently used to provide lateral resistance. These systems alter basic periods, damping, and structural stiffness in different ways, indicating that the direction of excitation may have a significant impact on how they interact with pulse-like ground motions. However, limited research has systematically measured whether stiffness-based systems increase orientation-dependent variability in structural response or whether damping-based systems consistently

lower displacement demands under rotational pulse-like loading.

To address these gaps, this study systematically evaluates how different lateral force-resisting systems respond to rotated pulse-like ground motions in a tall reinforced concrete building. Four structural configurations are considered: a regular moment-resisting frame (RB), a centrally located core shear-wall system (BS), a fluid viscous damper system (BF), and a combined shear-wall and fluid viscous damper system (BSF). Seven pulse-like ground motions recorded during the 2023 Türkiye earthquake are rotated from 0° to 180° at 3° intervals, and the resulting orientation-dependent roof displacement response is evaluated using time-history analysis. The governing roof displacement at each orientation is defined from the peak responses in the two principal directions. Complementary performance measures are then used to characterise directional dispersion, relative system effectiveness, exceedance vulnerability, and worst-case amplification. The principal contribution of the study is the systematic comparison of stiffness-dominated, damping-dominated, and combined lateral systems within a common rotation-based framework, rather than the rotation of ground motions itself. The study further relates the observed directional response to the dominant pulse period and structural fundamental period to examine how pulse characteristics influence the relative performance of the structural systems.

2. Ground motion details

In the present study, seven PL ground motions from the recent 7.6 Mw Turkey earthquake that occurred on 6th February 2023 were considered. The ground motion data were obtained from the Earthquake Disaster and Emergency Management Authority (AFAD) of Türkiye. The classification of ground motions is performed based on the Pulse Indicator (r) [20]. The seven records were selected from the Mw 7.6 Türkiye earthquake, and the pulse indicator was the sole criterion used to identify the pulse-like components. No additional screening criteria based on source-to-site distance, site class, V_{s30} , PGA, PGV, or recording quality were imposed. According to the classification, ground motions with an r value greater than or equal to 0.65 were classified as Pulse-Like (PL), while those with an r value less than 0.55 were classified as Non-Pulse-Like (NPL), and those with an r value between 0.55 & 0.65 were classified as Ambiguous. The two orthogonal horizontal components at each station were assessed independently. For the present study, a bidirectional ground-motion record was retained when at least one of the two orthogonal horizontal components satisfied the PL classification criterion. The corresponding orthogonal horizontal component was retained as the companion component so that the recorded two-component ground motion could be applied simultaneously during the time-history analysis. Thus, the term pulse-like record refers to the

bidirectional record pair selected based on the pulse-like classification of at least one horizontal component, rather than requiring both components to independently satisfy the PL criterion. The dominant pulse period reported for each record pair corresponds to the extracted pulse period of the component identified as pulse-like. The ground motions were downloaded directly from the AFAD database and were used in their original recorded form. No amplitude scaling or spectral matching was applied before the time-history analysis [21]. This approach preserves the recorded amplitude, frequency content, and relative characteristics of the two horizontal components and allows the orientation-dependent structural response to be evaluated without modification of the recorded ground motions. Table. 1 summarises key ground motion characteristics such as the Epicentral distance (Repi), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Pulse Indicator (r), and the time-averaged shear-wave velocity in the top 30 meters (Vs30) values.

The Vs30 values of the selected recording stations are also included in Table 1 to document the site conditions. Although Vs30 was not used as an additional criterion for selecting the pulse-like ground motions, reporting the site condition provides additional information for interpreting the variability in the recorded ground motions. Fig. 1 presents the

pulse extraction for the seven selected pulse-like ground motions. The adopted dominant pulse periods in the seven selected records range from 3.58 s to 3.98 s, indicating long-period pulse characteristics in comparison to typical fundamental periods of tall RC buildings. This range is especially useful for assessing displacement-driven structural response during pulse-like excitation.

To capture orientation-dependent demand, each bidirectional ground motion pair was rotated incrementally from 0° to 180° at 3° intervals, yielding 61 orientations per ground motion. Because of the symmetry of bidirectional excitation, rotation beyond 180° results in redundant responses [19]. The rotated acceleration components were computed using the standard coordinate transformation that can be seen in Eq. (1).

$$\begin{bmatrix} a_1(t, \theta) \\ a_2(t, \theta) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} a_{NS}(t) \\ a_{EW}(t) \end{bmatrix} \quad (1)$$

where $a_1(t, \theta)$ and $a_2(t, \theta)$ are the rotated acceleration components, $a_{NS}(t)$ and $a_{EW}(t)$ are the original components of ground motions, respectively, and θ represents the angle of rotation. Fig. 2 shows the variation of PGA and PGV due to directionality, and an obvious symmetrical response can be observed.

Table 1. Pulse-like ground motions

Station No.	Station Code	Epicentral Distance (km)	Direction	PGA (m/s ²)	PGV (m/s)	Pulse Indicator (r)	Pulse Type	Vs30 (m/s)
1	4631	21.43	EW	3.92	0.93	0.81	PL	543
			NS	3.26	0.47	0.42	NPL	
2	0133	126.52	EW	0.79	0.18	0.65	PL	548
			NS	0.45	0.14	0.49	NPL	
3	0134	126.52	EW	0.47	0.18	0.53	NPL	548
			NS	0.53	0.13	0.78	PL	
4	4404	143.46	EW	0.48	0.11	0.74	PL	1380
			NS	0.45	0.13	0.49	NPL	
5	2310	148.39	EW	0.55	0.05	0.65	PL	535
			NS	0.41	0.07	0.26	NPL	
6	0142	152.11	EW	0.23	0.12	0.66	PL	648
			NS	0.26	0.11	0.52	NPL	
7	0130	166.46	EW	0.8	0.24	0.32	NPL	330
			NS	0.79	0.23	0.71	PL	

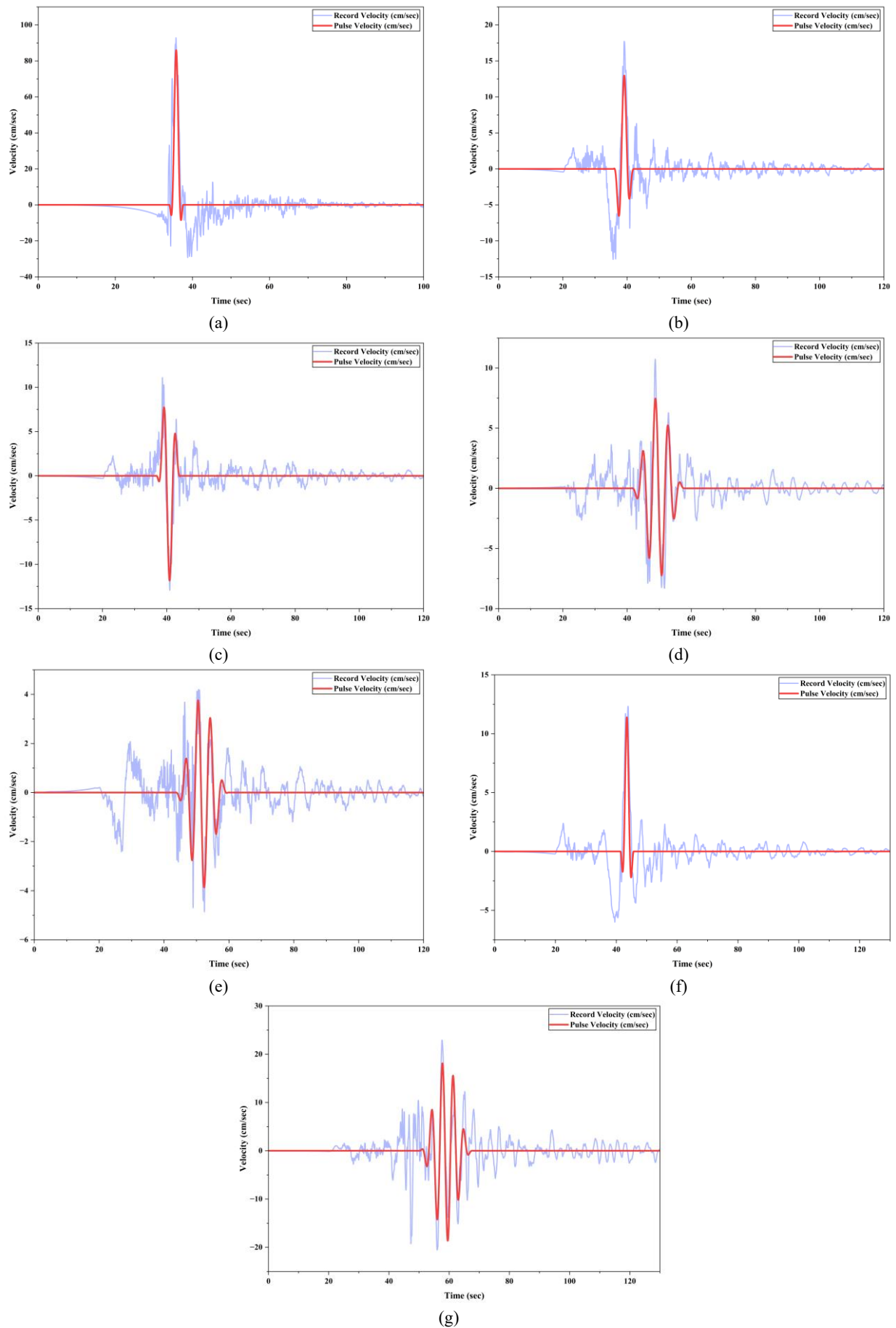


Fig. 1. Pulse extraction of the selected pulse-like ground motions: (a) GM 4631, (b) GM 0133, (c) GM 0134, (d) GM 4404, (e) GM 2310, (f) GM 0142, and (g) GM 0130

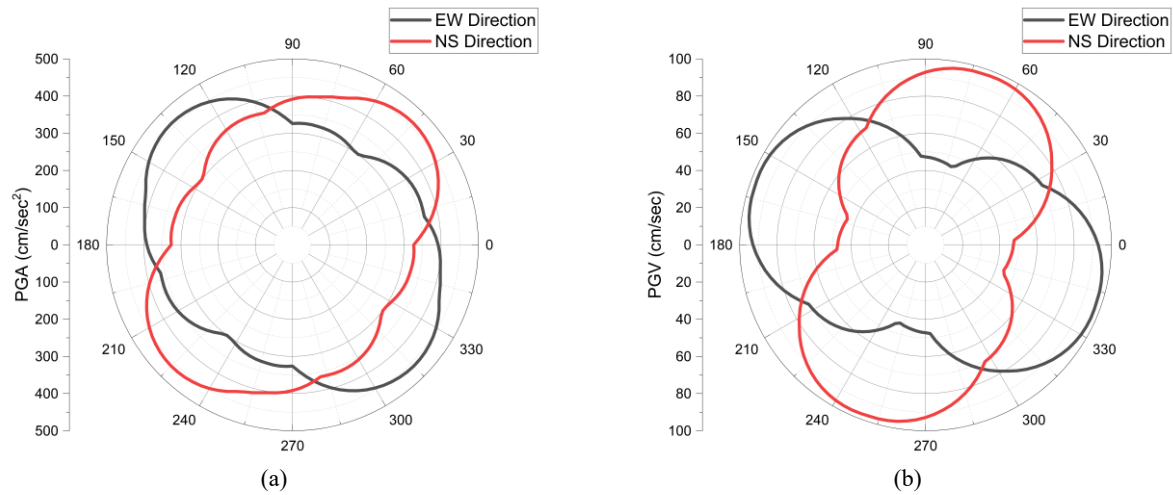


Fig. 2. Variation of a) PGA and b) PGV in both EW and NS directions

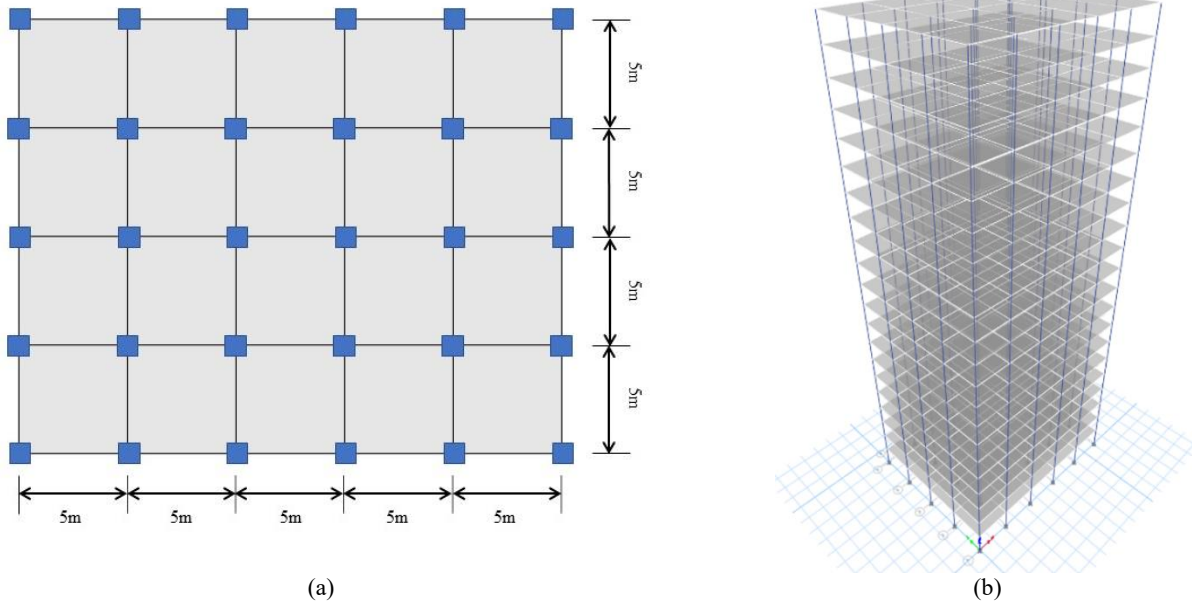


Fig. 3. Structures: a) Plan, and b) Elevation considered in the study

3. Numerical modelling

This study examines a G+20 RC structure, 63 meters tall (3 m at each floor), with 5 bays in the X-direction and 4 bays in the Y-direction, as shown in Fig. 3, to examine the impact of ground motion directionality on tall structures. Columns with a cross-section of $0.6 \text{ m} \times 0.6 \text{ m}$, a beam of $0.4 \text{ m} \times 0.6 \text{ m}$, and a slab thickness of 0.15 m were considered. The building's geometric properties were considered from the literature [22]. M50 grade of concrete and Fe500 grade of steel were considered. For evaluating a chosen structure, the Extended Three-Dimensional Analysis of Building System (ETABS), a commercially available finite element program, is employed. A constant inherent structural damping ratio (5% critical damping) is assumed for the RC components. Beam elements are employed to discretise columns and beams, whereas shell elements are utilised for the generation of the concrete slab. A shear wall of 0.2 m thickness was considered. The damper capacity was selected through a preliminary parametric evaluation of alternative Fluid Viscous Damper (FVD)

capacities, with emphasis on obtaining a stable time-history response without introducing excessive damper force demand. Based on this preliminary evaluation, a nominal capacity of 250 kN was adopted consistently for all FVD elements in the BF and BSF configurations. The same damper properties were used throughout the analyses to ensure a consistent basis for comparison between the damping-based and combined systems. The FVDs were modelled using Damper–Exponential link elements directly connected between the corresponding structural joints. A mass of 44 kg was assigned to each damper link, and an initial stiffness of zero was assigned in the U1 direction. The stiffness used for the stiffness-proportional viscous damping component was defined as the initial stiffness, with a modification factor of 1. FVDs provide additional energy dissipation through velocity-dependent damping forces, thereby reducing structural displacement and acceleration without intentionally introducing elastic stiffness in the active direction [23]. The shear wall is placed at the core [24], and FVDs are placed at

the corners on all floors, as they perform effectively against lateral loads [25]. As there are 21 floors and 4 corners in the structure, the number of FVDs used is 168 (i.e., 2 dampers at each corner) with the above-mentioned capacity.

Time-history analyses were performed using the Fast Nonlinear Analysis (FNA) procedure available in ETABS to evaluate the structural response under the rotated ground motions. The RC beams, columns, shear-wall components, and FVD link elements were modelled using linear properties. No explicit nonlinear hinges, distributed plasticity, or other material nonlinearities were assigned to the RC structural components. A rigid diaphragm was assigned at each floor level. P-Delta effects were not included in the time-history analyses. The same modelling assumptions were applied to all four structural configurations to maintain a consistent basis for comparing their orientation-dependent seismic responses. The potential influence of geometric nonlinearities and inelastic structural behaviour on the response of tall buildings is recognised as a limitation of the present study. Four structural configurations: i) Regular building (RB), i.e., Moment-resisting frame without additional lateral systems; ii) Shear Wall System (BS), i.e., Core shear wall with a thickness of 0.20 m placed centrally to enhance lateral stiffness; iii) Fluid Viscous Damper System (BF), i.e., Velocity-dependent dampers installed at all four corners of each floor; and iv) Combined System (BSF), i.e., Core shear wall combined with corner-installed FVDs. Table 2 summarises the fundamental translational periods of the four configurations considered. The inclusion of the shear wall substantially reduces the fundamental period because of the additional lateral stiffness, while the BF configuration exhibits a reduction in the reported fundamental period from 2.32 s to 1.89 s. Because the FVDs were assigned zero initial stiffness in the active U1 direction, this period difference is not interpreted as a direct stiffness contribution from the velocity-dependent viscous damping behaviour. These period shifts are especially relevant in the context of pulse-like ground motions with dominant pulse periods ranging from 3.58 to 3.98 s, allowing for the investigation of pulse-structure interaction effects under rotated excitation. Time-history analyses are performed for all four configurations under each rotated ground motion to assess the orientation-dependent roof displacement response. Roof displacement was selected as the primary engineering demand parameter because the present study focuses on orientation-dependent displacement response under pulse-like ground motions [26]. Pulse-dominated excitations can produce pronounced displacement demands in tall buildings, making roof displacement a direct measure for comparing the influence of ground-motion orientation and the relative effectiveness of the four structural configurations. Inter-story drift ratio and floor acceleration provide additional measures of structural performance. These

parameters represent complementary deformation- and acceleration-based measures, respectively, whereas the present study focuses specifically on orientation-dependent roof displacement demand. However, their evaluation is beyond the scope of the present study. Therefore, the conclusions presented in this study are limited to the orientation-dependent roof displacement response.

4. Directional performance evaluation

A rotation-based evaluation process is used to measure orientation-dependent structural demand. A set of complementary performance indicators is put together to describe directional dispersion, relative system effectiveness, exceedance vulnerability, and extreme amplification after the time-history response has been performed to obtain the governing displacement at each excitation angle.

4.1. Rotation response metric

Because the peak responses in the orthogonal directions do not typically occur simultaneously, the governing roof displacement at each rotation angle is calculated as the maximum of the absolute peak responses in the two principal directions. Accordingly, for each ground motion (i), structural system (j), and rotation angle (θ), the governing displacement demand is expressed as in Eq. (2)

$$D_{i,j}(\theta) = \max(|u_x^{max}|, |u_y^{max}|) \quad (2)$$

where, $D_{i,j}(\theta)$ is the roof displacement for each rotation angle, and u_x^{max} and u_y^{max} are the peak roof displacements in X and Y directions, respectively.

The adopted measure represents the maximum peak displacement demand among the two principal structural directions at each excitation orientation. It is selected to provide a consistent scalar measure for comparing orientation-dependent displacement demand among the four structural configurations. This measure should be distinguished from the maximum instantaneous resultant roof displacement, which requires simultaneous X- and Y-direction displacement histories. Accordingly, the directional performance indices presented in the subsequent sections are based on the governing peak directional roof displacement defined above.

Table 2. Summary of fundamental translational periods of structures

Structural Configuration	T ₁ in X direction (s)	T ₁ in Y direction (s)
Regular Frame (RB)	2.32	2.26
Shear Wall System (BS)	1.68	1.48
Fluid Viscous Damper (BF)	1.89	1.84
Combined System (BSF)	1.58	1.47

4.2. Directional performance indices

To assess directional variability and system performance, complementary indices based on dispersion, normalisation, exceedance, and extreme amplification are employed. These measures are used to characterise different aspects of orientation-dependent structural response and are consistent with established approaches for directional amplification and relative performance assessment [2,27,28]. The indices are evaluated for each ground motion and structural configuration using the 61 orientation-dependent displacement values.

4.2.1. Directional sensitivity index (DSI_e)

Directional dispersion is calculated using a percentile-based measure using Eq. (3). This index measures the relative spread of orientation-dependent demand while staying resistant to extreme outliers [29]. Higher values suggest increased sensitivity to excitation orientation.

$$DSI_e = \frac{D_{95} - D_5}{D_{50}} \quad (3)$$

where D_5 , D_{50} , and D_{95} , represent the 5th, 50th (median), and 95th percentile roof displacements across all rotation angles, respectively.

4.2.2. Normalised system effectiveness ratio (NSER)

To evaluate relative performance compared with the reference building (RB), the normalised system effectiveness ratio is calculated using Eq. (4). If the value of NSER is less than 1, it indicates improvement compared to the reference building, and if the value of NSER is greater than 1, indicating amplification as compared to the reference building. The mean, minimum, and maximum NSER values are used to assess both average performance and worst-case amplification behaviour.

$$NSER_{i,j}(\theta) = \frac{D_{i,j}(\theta)}{D_{i,RB}(\theta)} \quad (4)$$

where, $D_{i,RB}(\theta)$ is the governing displacement of the regular frame under the same ground motion and rotation angle.

4.2.3. Directional vulnerability index (DVI)

A displacement-based threshold is established for every ground motion as the maximum displacement of the reference building in all orientations to measure exceedance vulnerability under directional excitation. Eqs. (5) and (6) are used to determine the reference building's maximum displacement in all orientations and the directional vulnerability index, respectively. By measuring the percentage of orientations that result in demand that is higher than the baseline worst-case response, this metric quantifies the frequency of exceedance as opposed to single extreme amplification.

$$D_{lim,i} = \max_{\theta} D_{i,RB}(\theta) \quad (5)$$

$$DVI_{i,j} = \frac{N_{\theta} [D_{i,j}(\theta) > D_{lim,i}]}{61} \quad (6)$$

where, $D_{lim,i}$ is the maximum displacement RB over all orientations, and N_{θ} represents the number of rotation angles for which the system displacement exceeds the worst-case displacement of the reference building.

4.2.4. Worst-case amplification factor (WCAF)

To determine the most critical orientation-driven amplification, Eq. (7) is utilised to compute the worst-case amplification factor. A direct indicator of the worst directional performance scenario, this metric shows the highest relative amplification seen across all ground motions and orientations.

$$WCAF_j = \max_{i,\theta} (NESR_{i,j}(\theta)) \quad (7)$$

4.3. Pulse-structure interaction parameter

To mechanistically understand directional response trends, Eq. (8) is used to determine the Pulse Ratio (λ) between the dominant pulse period (T_p) and the structural fundamental period (T_1). The basic periods of the structural configurations for the chosen records range from 1.47 s to 2.32 s, whereas the dominant pulse periods range from 3.58 s to 3.98 s. As a result, $\lambda > 1$ in every instance, indicating that the dominant pulse periods are longer than the fundamental periods of the considered structural configurations. This period relationship provides a useful basis for interpreting the pulse-related displacement response; however, $\lambda > 1$ alone does not establish exclusive pulse dominance or rule out other dynamic response mechanisms.

$$\lambda = \frac{T_p}{T_1} \quad (8)$$

5. Results

The time-history analyses were performed for all four structural configurations under the rotated pulse-like ground motions to evaluate orientation-dependent displacement demand and system performance. The results are presented in terms of governing roof displacement, directional sensitivity, relative system effectiveness, exceedance vulnerability, and worst-case amplification behaviour under varying excitation orientations.

5.1. Orientation-dependent roof displacement

Time-history analyses were performed for all four structural configurations using rotated ground motions. The governing roof displacement was calculated using the orientation-based definition provided in the previous section. Representative displacement-rotation curves in all systems exhibit considerable orientation-dependent variability. For each record, the highest displacement does not necessarily occur along the key structural axes at 0° to 90°, indicating that

excitation alignment, rather than geometric axes, determines critical demand. This observation is consistent with earlier research, which indicates that rotating ground motions may cause a stronger structural reaction than standard fault-parallel or fault-normal orientations [19]. Across the dataset, directional variation in roof displacement stays consistent and symmetric about 180° , indicating the consistency of the rotation procedure. Fig. 4 displays the orientation-dependent variation in governing roof displacement across all structural configurations using the representative GM 4631, which resulted in the largest amplification in the dataset.

5.2. Directional sensitivity

The DSI_e , which is based on percentiles, was used to measure directional sensitivity. To describe response variability while reducing sensitivity to extreme outliers, percentile-based dispersion methods are frequently employed [29]. The average DSI_e values for the regular frame, BF, BS, and BSF are 0.212, 0.188, 0.318, and 0.313, respectively, over the seven records. The highest directional dispersion is observed in the BS and BSF configurations, where the maximum DSI_e for individual records can reach 0.52. The BF, on the other hand, exhibits the least amount of dispersion between orientations. These findings show that damping-dominated configurations lessen the dispersion of displacement demand across rotation angles, whereas stiffness-dominated systems exhibit more orientation-dependent variability. The comparative directional dispersion across structural configurations is summarised in Fig. 5.

5.3. Normalised system effectiveness ratio

The NSER was calculated for each orientation and ground motion to assess relative performance in relation to the RB. The mean NSER values are 0.858 for BF, 0.748 for BS, and 0.731 for BSF. Because NSER values are less than one, all enhanced systems lower the average roof displacement in comparison to the RB. The average decrease offered by the BS and BSF is higher than that of the damper-only setup. Nonetheless, all systems exhibit orientation-dependent amplification. For BF, the maximum NSER value is 1.336; for BS, it is 1.180; and for the BSF, it is 1.172. The results show that any enhanced system can produce a displacement demand greater than that of the regular frame under certain orientations. Under GM 4631 at a rotation angle of 6° , the fluid viscous damper arrangement exhibits the maximum amplification of 33.6%. Fig. 6 presents the variation of the Normalised System Effectiveness Ratio with rotation angle for the representative GM 4631.

To assess whether the observed differences among the structural configurations were statistically meaningful, paired Wilcoxon signed-rank tests were performed using the corresponding record-level results. For DSI_e , statistically significant differences were observed between BF and BS and between BF and BSF ($p = 0.0156$) for both comparisons. However, the difference between BS and BSF was not

statistically significant ($p = 0.9375$), indicating that their mean DSI_e values of 0.318 and 0.313, respectively, are statistically comparable. The comparisons involving RB were also not statistically significant ($p > 0.05$). For NSER, all pairwise comparisons among BF, BS, and BSF were statistically significant ($p < 0.001$). The DSI_e comparisons were based on the seven record-level values for each configuration, whereas the NSER comparisons used the corresponding orientation-level paired values.

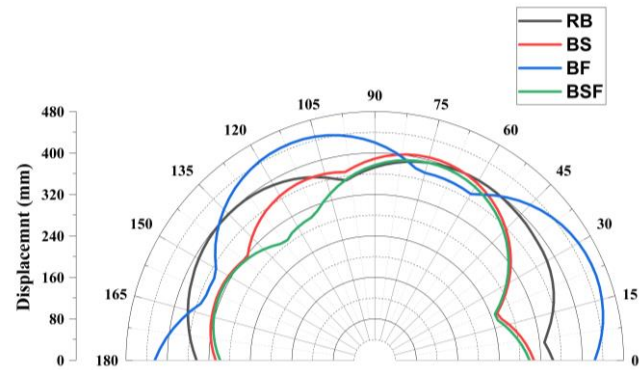


Fig. 4. Governing roof displacement as a function of rotation angle for GM 4631

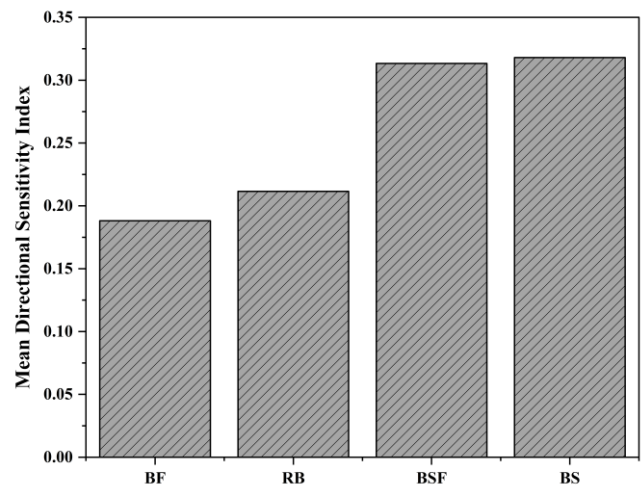


Fig. 5. Mean directional sensitivity index for the four structural configurations

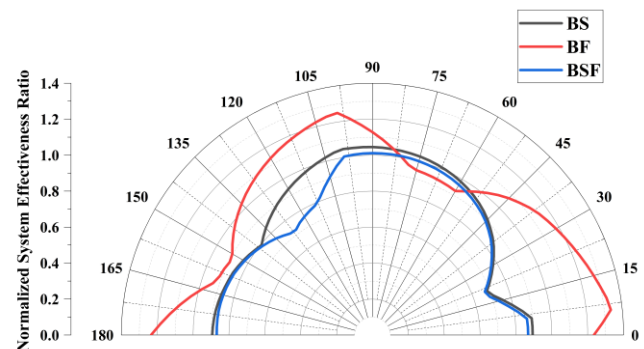


Fig. 6. Variation of normalised system effectiveness ratio with rotation angle for GM 4631

5.4. Directional vulnerability

The DVI is calculated to evaluate directional vulnerability. The percentage of orientations that result in displacement over the RB's worst-case reaction is measured by this index. Throughout the dataset, the BF mean DVI value is 0.171, the BS value is 0.040, and the BSF value is 0.026. With one record displaying exceedance across around 66% of orientations, the BF configuration has the highest exceedance frequency. On the other hand, the BSF and BS have shown significantly reduced exceedance probabilities. The relative exceedance vulnerability of the systems is summarised in Fig. 7. These findings show that, in comparison to stiffness-dominated systems, the BF has a higher orientation-dependent exceedance vulnerability even while it decreases directional dispersion.

5.5. Worst-case amplification

Extreme directional sensitivity is measured by the Worst-Case Amplification Factor, which is the global maximum NSER over all records and orientations. The BF under GM 4631 at 6°, the BS under GM 2310 at 87°, and the BSF under GM 2310 at 87° have the determined WCAF values of 1.336, 1.180, and 1.172, respectively. The dominant pulse period of this record is 3.98 s, which is longer than the fundamental periods of all the considered structural configurations. This period relationship indicates that the critical BF response occurs under an excitation with a dominant long-period pulse relative to the structural fundamental period. However, the period ratio alone does not establish a unique response mechanism or exclude other dynamic effects. Therefore, the observed amplification is interpreted as an orientation-specific response under pulse-like excitation rather than as definitive evidence of a resonance-free pulse mechanism. The critical orientation differs among the structural configurations because the same rotated ground motion interacts differently with each lateral force-resisting system. Although the bidirectional ground-motion pair and rotation range are identical for all configurations, the structural response to the two horizontal components is influenced by the system-specific dynamic characteristics and lateral stiffness or damping properties. The BS and BSF configurations introduce additional lateral stiffness through the core shear wall, whereas the BF configuration provides velocity-dependent energy dissipation. Consequently, the orientation associated with the maximum roof displacement can vary among RB, BS, BF, and BSF. This system-dependent critical response cannot be inferred solely from the characteristics of the ground motion or from a single excitation direction. The mean NSER of BF remains below unity, indicating an overall reduction in roof displacement relative to RB, while the WCAF and DVI results demonstrate that this reduction is not uniform across all excitation orientations. The results therefore indicate that additional damping can reduce average directional variability without necessarily preventing

localised displacement amplification under particular pulse-alignment conditions. The directional performance metrics for all structural configurations are summarised in Table 3.

5.6. Ground motion-dependent system performance

The effectiveness of the structural systems varies substantially across the considered pulse-like ground motions, indicating that system performance depends strongly on ground motion characteristics and directional pulse effects. Table 4 summarises the maximum roof displacement response and the percentage reduction relative to the regular frame for all structural configurations. The results indicate that no single structural system consistently provides the best performance for all pulse-like motions, demonstrating the importance of motion-dependent evaluation in tall building seismic assessment.

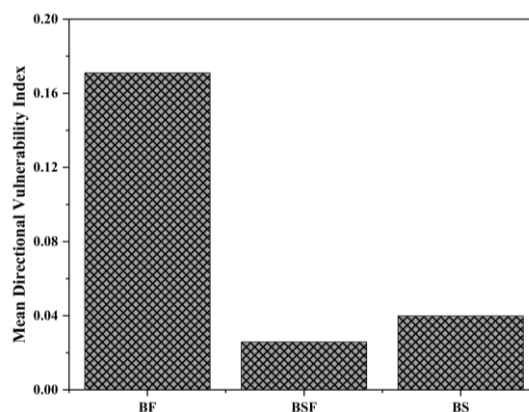


Fig. 7. Mean directional vulnerability index for the structural configurations

Table 3. Summary of directional performance metrics

System	Mean DSI _e	Mean NSER	Mean DVI	WCAF
RB	0.212	-	-	-
BS	0.318	0.748	0.040	1.180
BF	0.188	0.858	0.171	1.336
BSF	0.313	0.731	0.026	1.172

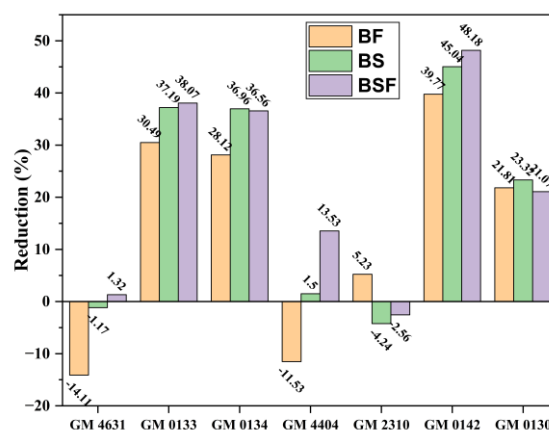


Fig. 8. Percentage reduction in maximum roof displacement relative to the regular frame for all structural configurations and ground motions considered

Table 4. Ground motion characteristics and percentage reduction in maximum roof displacement relative to the regular frame

GM ID	PGA (m/s ²)	PGV (m/s)	Pulse Period (s)	BF Reduction (%)	BS Reduction (%)	BSF Reduction (%)
4631	3.92	0.93	3.98	-14.11	-1.17	1.32
0133	0.79	0.18	3.98	30.49	37.19	38.07
0134	0.53	0.13	3.98	28.12	36.96	36.56
4404	0.48	0.11	3.98	-11.53	1.5	13.53
2310	0.55	0.05	3.98	5.23	-4.24	-2.56
0142	0.23	0.12	3.82	39.77	45.04	48.18
0130	0.79	0.23	3.58	21.81	23.32	-21.07

The combined shear wall-fluid viscous damper system demonstrates the most consistent overall displacement reduction behaviour across the majority of the considered ground motions. For moderate pulse intensity motions such as GM 0133, GM 0134, and GM 0142, the shear wall and combined systems produce substantial displacement reduction, with displacement reductions exceeding 45% for some ground motions. In contrast, the fluid viscous damper system exhibits comparatively lower reduction for several motions and produces displacement amplification under specific pulse-dominated cases. For GM 4631, which is associated with the highest PGA and PGV values, the fluid viscous damper system increases displacement demand by approximately 14% relative to the regular frame, whereas the shear wall and combined systems provide only marginal reduction. Similar amplification behaviour is also observed for GM 4404, indicating that damping-based systems remain sensitive to directional pulse alignment and long-period displacement demand.

Fig. 8 presents the percentage reduction in maximum roof displacement for all structural configurations and ground motions. The results further indicate that the combined system provides comparatively stable response reduction across varying motion characteristics, whereas the effectiveness of the individual shear wall and fluid viscous damper systems varies substantially depending on pulse characteristics and directional excitation effects. For lower displacement demand cases such as GM 2310, the fluid viscous damper system demonstrates improved effectiveness relative to the stiffness-dominated systems. The results suggest that the relative efficiency of stiffness-based and damping-based systems is governed by the combined influence of pulse characteristics, directional response behaviour, and displacement demand rather than a single intensity measure alone.

6. Discussion

The findings in Section 5 make it evident that the displacement demand varies with orientation for each of the considered structural configurations. In the context of structural period variation, pulse–structure interaction, and

the opposing functions of stiffness enhancement and additional damping, these results are interpreted in this section. In particular, the influence of directional dispersion and exceedance behaviour on system robustness under pulse-like excitation is discussed, along with the connection between fundamental structural period and dominant pulse period of ground motion.

6.1. Influence of structural period and pulse characteristics

The four structural configurations have different fundamental period characteristics. The RB has fundamental periods of roughly 2.32 s and 2.26 s in the two primary directions. The addition of shear walls substantially decreases these values due to increased stiffness, whereas fluid viscous dampers result in a slight period reduction. The combined system creates periods similar to those of the shear wall design. The selected pulse-like ground motions have dominant pulse periods ranging from 3.58 to 3.98 s. Consequently, the ratio of dominant pulse period to structural fundamental period exceeds unity for all investigated configurations. This indicates that the dominant pulse characteristics occur at periods longer than the fundamental structural periods and provides a useful basis for interpreting the observed displacement response. However, the period ratio alone is insufficient to establish that the response is exclusively governed by pulse effects or to rule out other dynamic mechanisms. The results are therefore interpreted as indicating an influence of long-period pulse characteristics on orientation-dependent displacement demand rather than as evidence that other dynamic mechanisms are absent. The relation between the dominant pulse period and the structural fundamental period is demonstrated in Fig. 9.

Previous research on pulse-driven structural responses revealed comparable pulse–structure interaction behaviour [30,31]. In this context, the observed displacement response is interpreted as being influenced by the high-amplitude velocity-pulse characteristics of the selected motions rather than being attributed solely to resonance at the fundamental mode. For the investigated configurations, modifying structural stiffness did not uniformly reduce the vulnerability to pulse alignment.

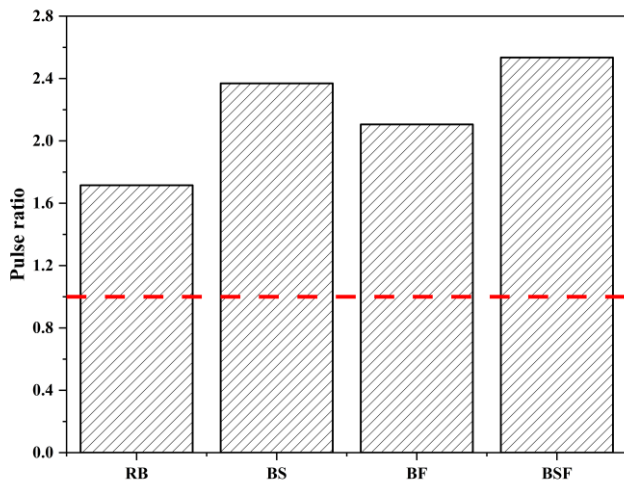


Fig. 9. Ratio of dominant pulse period to structural fundamental period for each configuration

6.2. Comparative behaviour of damping and stiffness-based systems

The BS and BSF configurations exhibit the highest mean directional sensitivity among the investigated systems. This phenomenon is caused by the anisotropic stiffness distribution of the core shear wall structure. Although the building layout remains rectangular, stiffness improvement along principal axes highlights dynamic response differences as excitation orientation varies. Previously, orientation-dependent spectral features have been associated with directional variability in structural demand [2,27]. Under certain orientations, BF shows increased exceedance despite having lower directional dispersion. This apparent amplification should be interpreted relative to the RB rather than as energy generation by the dampers. The mean NSER of BF is 0.858, indicating an overall reduction in roof displacement; however, the NSER reaches 1.336 for GM 4631 at a rotation angle of 6° . This behaviour may be associated with the interaction between the rotated bidirectional pulse and the velocity-dependent damping characteristics of the FVD system, as rotation changes the relative contribution of the two horizontal ground-motion components and consequently alters the structural response experienced by the damping system. The resulting damping benefit can therefore vary with excitation orientation. For GM 4631, the dominant pulse period of 3.98 s is substantially longer than the BF fundamental period of approximately 1.89 s, indicating a long-period pulse relative to the structural period. This period relationship provides a useful basis for interpreting the observed response, but it does not by itself establish exclusive pulse dominance or rule out other dynamic response mechanisms. Thus, supplementary damping reduces the average displacement and directional dispersion but does not necessarily suppress the displacement demand at every orientation. The BSF exhibits comparatively balanced behaviour, combining overall displacement reduction with lower exceedance vulnerability. Although directional dispersion is not eliminated, the combination of energy

dissipation and stiffness improvement restricts severe amplification. The findings show that the relative performance of stiffness- and damping-based systems can vary with excitation orientation and pulse characteristics. The findings suggest that design evaluation based on a single excitation orientation may underestimate critical displacement demand in tall buildings subjected to pulse-like motions. The findings of this study should be interpreted within the scope of the investigated structural and ground-motion characteristics. The analysis considers a single 21-story rectangular RC building and seven pulse-like ground motions from the 2023 Türkiye earthquake. Therefore, the quantitative values of directional sensitivity, system effectiveness, and worst-case amplification should not be considered universally applicable to buildings with different heights, aspect ratios, or structural layouts. Nevertheless, the observed system-dependent changes in orientation sensitivity demonstrate the importance of considering ground-motion rotation when evaluating stiffness- and damping-based systems under pulse-like excitation. Further studies involving buildings with different geometries, heights, structural layouts, and broader ground-motion datasets are required to assess the generality of these trends.

7. Conclusions

This study investigated the influence of ground motion directionality on the orientation-dependent roof displacement response of a single G+20 reinforced concrete building (63 m high) subjected to seven pulse-like ground motions recorded during the 2023 Turkey earthquake. Four structural configurations were evaluated: a regular moment-resisting frame, a shear wall system, a fluid viscous damper system, and a combined shear wall–damper system. Time-history analysis using the Fast Nonlinear Analysis procedure was used to analyse the bidirectional ground motions after rotation from 0° to 180° at 3° intervals. The governing roof displacement at each orientation was identified as the highest absolute peak response in the two principal directions. Dispersion, normalisation, and exceedance-based performance indicators were used to characterise directional variability and relative system effectiveness. The conclusions below are therefore limited to the investigated building configurations and the selected pulse-like ground-motion records.

1. For the investigated building configurations and selected pulse-like ground motions, roof displacement demand varies significantly with excitation orientation, and the maximum response does not necessarily occur along the principal structural axes.
2. For the investigated building and selected pulse-like ground motions, the stiffness-dominated shear wall and combined configurations exhibit higher directional dispersion than the regular frame and fluid viscous damper configurations.

3. For the investigated building and selected ground motions, the fluid viscous damper configuration reduces directional dispersion but exhibits the largest worst-case amplification and highest exceedance frequency under specific pulse-aligned orientations.
4. Within the investigated building and selected pulse-like ground motions, all enhanced systems may exceed the displacement demand of the regular frame under certain orientations, highlighting the importance of rotation-based evaluation.
5. For the selected pulse-like ground motions, the dominant pulse periods substantially exceed the fundamental periods of all four investigated structural configurations, indicating that the dominant pulse characteristics occur at periods longer than the fundamental structural periods. This period relationship provides a useful basis for interpreting the observed displacement response but does not, by itself, establish exclusive pulse dominance or rule out other dynamic response mechanisms.
6. Among the four investigated configurations, the combined shear wall-damper system provides comparatively balanced performance by limiting extreme amplification while maintaining overall displacement reduction across the selected ground motions.

The results of the present investigation demonstrate that directional pulse-structure interaction can alter the relative effectiveness of the investigated stiffness- and damping-based lateral systems, emphasising the value of orientation-dependent assessment in performance-based seismic design. From a practical engineering perspective, the results of the present investigation indicate that the selection and evaluation of lateral force-resisting systems for tall RC buildings subjected to pulse-like ground motions should consider excitation orientation rather than relying on a single ground-motion direction. For the investigated configuration, damping-based systems reduce average displacement and directional dispersion but may still experience increased demand at specific orientations. Rotation-based assessment can therefore help identify critical orientations and provide a more comprehensive basis for comparing stiffness- and damping-based systems under pulse-like excitation. These implications should be further evaluated using buildings with different geometries, heights, structural layouts, and broader ground-motion datasets.

Declarations

Conflict of interests

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Author contributions

Chaitanya Bhargav Nerella: Methodology, Investigation, Data curation, Data Analysis, Conceptualization, Writing – original Draft. Jayaprakash Vemuri: Conceptualization, Writing – Review & editing, Supervision. Sri Kalyana Rama Jyosyula: Conceptualization, Writing – Review & editing, Supervision. Rajaram Chenna: Conceptualization, Writing – Review & editing, Supervision.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Use of generative AI and AI-assisted technologies

The author(s) confirm that the author(s) did not use any AI tools in the preparation of this work/research/study.

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