

# The Impact of Vertical Seismic Component on Concrete Structures: Analysis and Design according to the Algerian Seismic Code (RPA 2024)

**Samah Hasrouri**

Department of Civil Engineering, Faculty of Technology, University of Batna 2, Algeria  
samah.hasrouri@univ-batna2.dz (corresponding author)

**Abdelkrim Kadid**

Department of Civil Engineering, Faculty of Technology, University of Batna 2, Algeria  
a.kadid@univ-batna2.dz

**Djarir Yahiaoui**

Department of Civil Engineering, Faculty of Technology, University of Batna 2, Algeria  
d.yahiaoui@univ-batna2.dz

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## ABSTRACT

This study examines the effect of vertical seismic components on Reinforced Concrete (RC) structures, specifically in the framework of the new Algerian seismic code (RPA 2024). Despite developments in the knowledge of horizontal ground motions, recent earthquakes, such as those in Turkey-Syria (2023) and Algeria (Béjaïa 2021-2022, Boumerdès 2003), have highlighted the significant contribution of vertical accelerations in amplifying structural damage. The current research evaluates low-rise (2-story), mid-rise (6-story), and high-rise (9-story) buildings under seven earthquake records scaled according to RPA 2024 specifications. Using nonlinear dynamic analysis, it advances current knowledge by providing insights into the specific effects of vertical ground motion on the evaluation of variations in internal forces, lateral displacements, and story-level responses, focusing on height-dependent effects, force redistribution, and displacement amplification factors. The results indicate that low-rise buildings (2-story) have negligible effects from combined Horizontal and Vertical (H+V) loading with variations of 5-15%, and mid-rise buildings (6-story) have moderate effects (20-30%). In contrast, high-rise buildings (9 stories) have significant height-dependent variations of 10-35%.

*Keywords-seismic load; vertical seismic load; concrete structures; nonlinear dynamic analysis*

## I. INTRODUCTION

The contribution of the vertical seismic component in concrete buildings is a fundamental aspect of seismic design, especially in countries like Algeria, where earthquakes are much more frequent. The Algerian Seismic Code (RPA 2024) [1] is being revised to correct previous shortcomings. Vertical ground motions can play a significant role in the seismic response of RC structures. This is evidenced by the increased internal forces, i.e. axial forces in columns and bending moments in beams, which necessitates the adaptation of existing design strategies to promote safety and structural integrity [2 - 4]. The consideration of vertical seismic effects was underestimated in design practice [5-9]. Research has shown that the vertical seismic component can cause colossal

amplifications of structural requirements; an element often overlooked by current seismic codes, such as the Eurocodes [10]. The Algerian seismic codes have historically focused on horizontal ground motions; however, recent studies underline the need for a more integrated approach that includes vertical components, especially for regions close to fault zones, where these effects are amplified [7]. A comparison with international standards, such as those of the United States and New Zealand, demonstrates that although these codes face difficulties in the implementation of vertical seismic effects, they serve as a reference point for the improvement of Algerian standards [6 - 8, 11]. The study highlights the importance of vertical ground motions in the seismic design of various structures, such as masonry domes and bridges, since vertical excitations tend to exacerbate damage and affect structural integrity. The

formulation of tailored design spectra and damping reduction factors for application to vertical members is essential to increase the accuracy and reliability of seismic analyses. Finally, the incorporation of vertical seismic effects in the Algerian Seismic Code (RPA 2024) is necessary to improve the safety and resilience of concrete structures exposed to seismic zones [5, 6- 8]. The present study analyzes the effects of combined H+V seismic loading on multi-story structures under the provisions of the newly implemented Algerian seismic code, RPA 2024. The seismic response of low-rise (2-story), mid-rise (6-story), and high-rise (9-story) structures subjected to both H and combined H+V earthquake components is evaluated. Using nonlinear dynamic analysis, the present paper assesses the structural response to seven different earthquake

records (Altade, Arrayo, Corral, Lucern, Newhal, Petrol, and Sylmar), each scaled according to the RPA 2024 code. The current work measures and compares the change in internal forces (moment, shear, and axial), lateral displacements, and story level responses for different building heights and loading conditions. In addition, this study evaluates the effects of incorporating vertical seismic components into the structural design, as required by RPA 2024, with particular emphasis given on height-dependent phenomena, force redistribution mechanisms, and displacement amplification factors. The purpose of this in-depth investigation is to improve the understanding of structural response to simultaneous seismic loads, thereby facilitating the review and application of the updated code provisions, as shown in Figure 1.

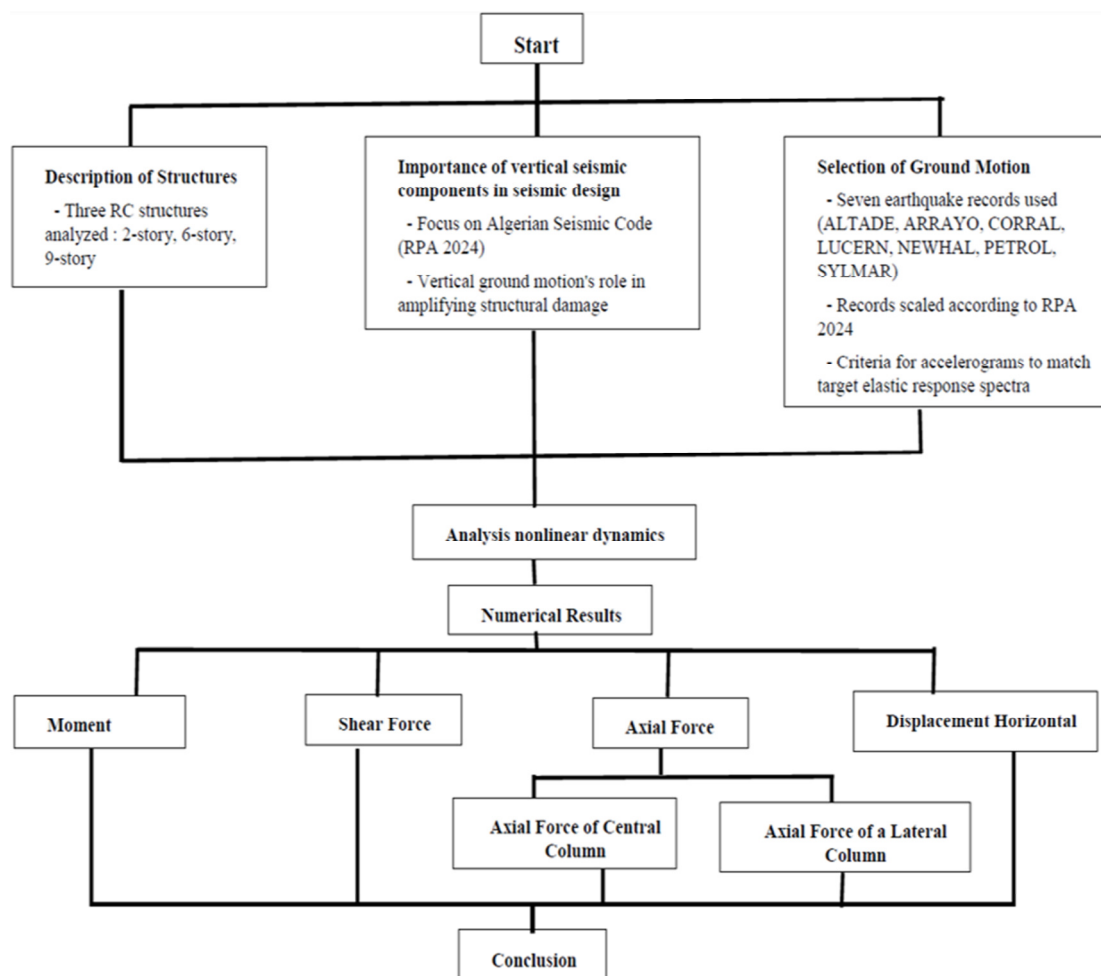


Fig. 1. Flowchart of the research study.

## II. DESCRIPTION OF THE STRUCTURES

The present study examined three RC structures: a 2-story, 6-story, and 9-story building. The 2-story structure was composed of uniform beams measuring  $30\text{ cm} \times 40\text{ cm}$  and  $6T_{14}$ , as well as columns measuring  $40\text{ cm} \times 40\text{ cm}$  and  $8T_{14}$ , which were present across both levels. The 6-story structure maintained consistent beam dimensions ( $30\text{ cm} \times 40\text{ cm}$ ,  $6T_{14}$ ), while columns were larger ( $50\text{ cm} \times 50\text{ cm}$ ,  $10T_{16}$ ). The 9-story

structure exhibited variable column dimensions and reinforcement, with the largest columns situated at the base ( $60\text{ cm} \times 60\text{ cm}$ ,  $10T_{16}$ , floors 1-3). These columns diminished in size to  $50\text{ cm} \times 50\text{ cm}$  ( $8T_{16}$ , floors 4-6) and  $40\text{ cm} \times 40\text{ cm}$  ( $8T_{14}$ , floors 7-9), while the beams remained constant at  $30\text{ cm} \times 40\text{ cm}$  ( $6T_{14}$ ) throughout the structure. This configuration is indicative of a progressive increase in column strength and size with increasing building height, while beam specifications remained constant, as portrayed in Figure 2.

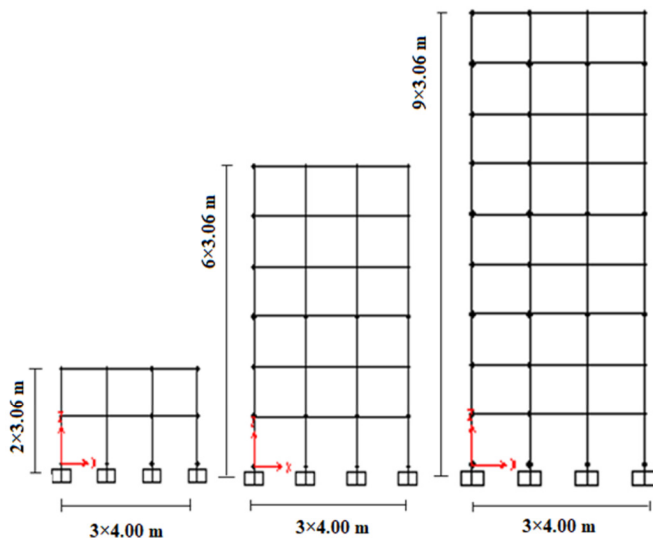


Fig. 2. The three RC structures.

The flexural deflection of RC members can be calculated using finite element analysis or plastic hinge methods. Finite element analysis is computationally intensive, especially for complex models, while plastic hinge methods are more efficient. In SAP2000, the Interaction PM3 Hinge model incorporates column plastic hinges with coupled behavior in orthogonal directions. Moment-curvature analysis and interaction diagrams are instrumental in determining column capacities and the associated rotations. The design of beam hinges is predicated on the principle of bending moments, with the properties of these elements delineated by FEMA 356 (2003) [12].

### III. SELECTION OF GROUND MOTION

The generation of artificial accelerograms is important to align with the target elastic response spectra specified in code RPA2024 for a damping ratio of 5%, while ensuring their duration corresponds to the seismic magnitude and site class associated with parameter A, also specified in code RPA2024. The series of accelerograms must adhere to the following criteria:

- The use of a minimum of seven accelerograms is required.
- The average response of the accelerograms must be utilized to determine the seismic action effects.
- The mean spectral acceleration at zero period, derived from the accelerograms, must equal or exceed the site-specific AIS value.

The period range of 0 is to be considered and is important for the average elastic response spectrum ( $\zeta = 5\%$ ) across all accelerograms, when plotted as a function of time ( $2T_0$  to  $2T_0$ , where  $T_0$  is the structure's fundamental period in the relevant direction), not to fall below 90% of the target spectrum in any interval. Furthermore, within the same period range, the elastic response spectrum ( $\zeta = 5\%$ ) of any individual accelerogram must not drop below 50% of the corresponding target spectrum value. These requirements ensure that the accelerograms, when

considered collectively and individually, capture the seismic demand while preserving compatibility with structural dynamics and site conditions. The seismic action's H+V components are presented in Figure 3.

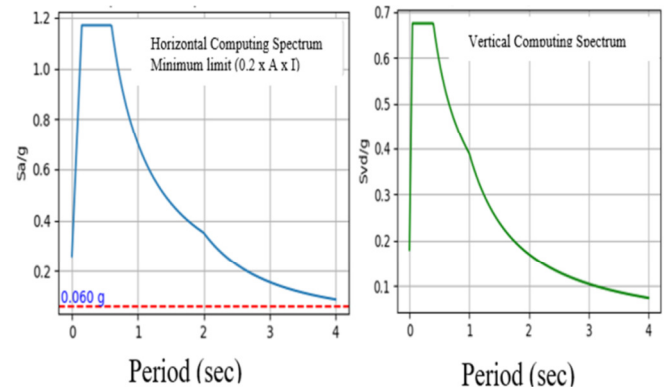


Fig. 3. Horizontal (left) and vertical (right) components of the seismic action.

## IV. RESULTS AND DISCUSSION

### A. Moment

Figures 4-6 illustrate a nonlinear analysis of 6-story and 2-story buildings subjected to Horizontal (H) and H+V earthquakes. The analysis indicates that there are significant changes in moments (15–50%) in various sections of structures with complex behavior. It was observed that Arrayo and Sylmar type earthquakes are associated with maximum changes, ranging from 30% to 70%. Moderate changes, with alterations ranging from 20% to 60%, were exhibited by Lucern and Petrol types. The Petrol indicator signifies constant fluctuations in moments between floors (25% – 40%), thereby exhibiting an even distribution of loads. As indicated by Altade and Corral, substantial alterations in the middle floors are observed, exhibiting considerable repercussions from the loads exerted in a vertical direction. These observations suggest that incorporating H+V earthquake loads in the design of tall buildings is necessary to enhance their strength and nonlinear behavior.

### B. Shear Force

Figures 7, 8, and 9 show the shear force behavior of 2-story, 6-story, and 9-story buildings, respectively, under earthquake conditions. The 2-story building exhibits minimal shear forces (-200 kN to +200 kN) that are distributed uniformly between H loads and H+V loads. The 6-story building has greater shear forces ( $\pm 400$  kN), which are largely based on various records and height. In comparison, the 9-story building exhibits a greater proportion of its shear force in the middle floors (4–6), with values reaching up to  $\pm 200$  kN. This result suggests that tall buildings are not significantly impacted by vertical loads, as evidenced by the comparable records and negligible difference observed between H and H+V loads. A review of the available records pertaining to seismic activity reveals that the Sylmar and Petrol regions typically exhibit maximum shear demands, while Lucern and Corral demonstrate medium responses. It was found that Altade

exhibited analogous behavior in all buildings. The findings of this study demonstrate a correlation between building height and characteristics, and the distribution of shear forces in structures during seismic events.

500%. The Altade, Corral, and Newhal areas demonstrate a more moderate scaling pattern, with an increase ranging from 350% to 400%. A close examination of the data reveals that Petrol displays the most consistent behavior, with an observed increase ranging from 250% to 300%. The disparities between H and H+V loading intensify with height, ranging from 25%–30% in the 2-story structure to 60%–70% in the 9-story structure, thereby emphasizing the height-dependent amplification of vertical loading effects. These trends signify the critical role of building height and seismic record characteristics in axial force distribution.

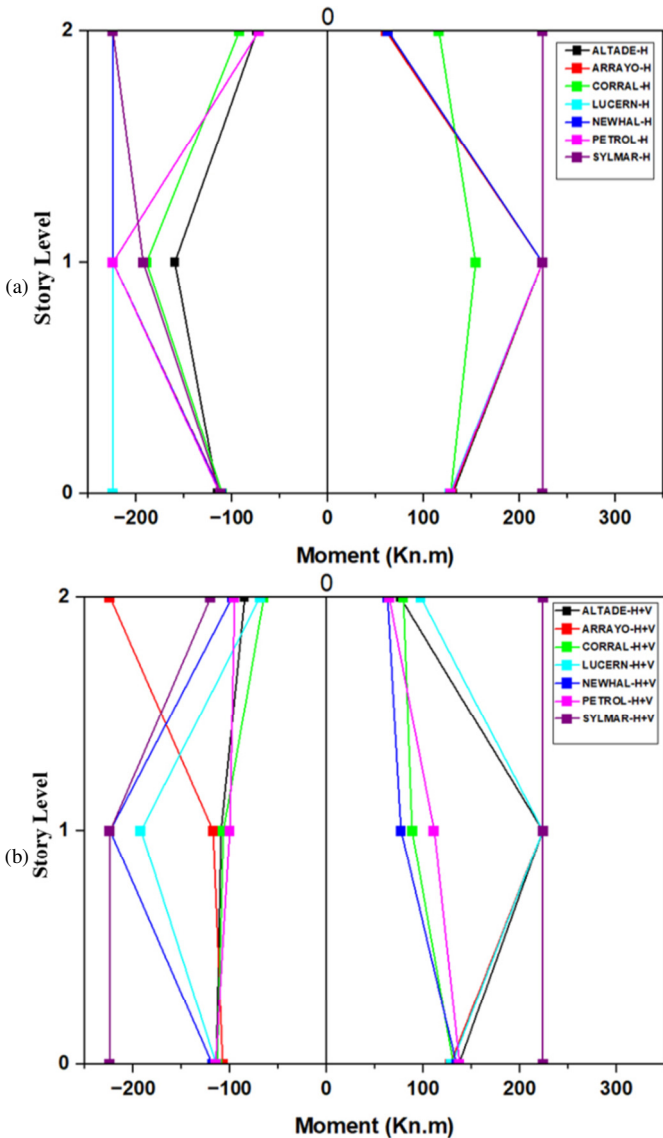


Fig. 4. Moment of the shore posts of a structure (a) under H and (b) H+V seismic loads for 2-story structure.

C. Axial Force of Central Column

Figures 10-12 present the axial force scale in a significant manner with building height, escalating from -100 kN to -500 kN in the 2-story structure to -1500 kN to -2000 kN (300%–400% increase) in the 6-story structure, and peaking at -2500 kN to -3000 kN (500%–600% increase) in the 9-story structure. A thorough examination of the seismic records reveals significant variations, displaying a notable increase in the number of stories in the Sylmar area, with a 700% surge from two to nine stories. This is followed by the Arrayo and Lucern areas, where there was an increase ranging from 450% to

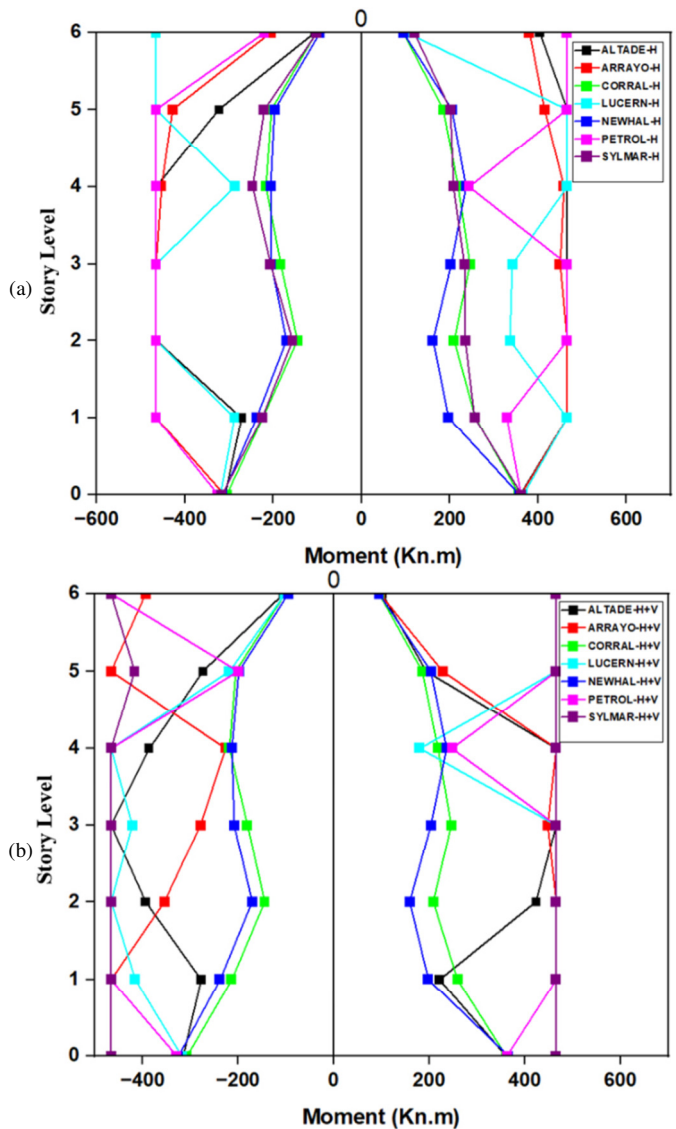


Fig. 5. Moment of the shore posts of a structure (a) under H and (b) H+V seismic loads for 6-story structure.

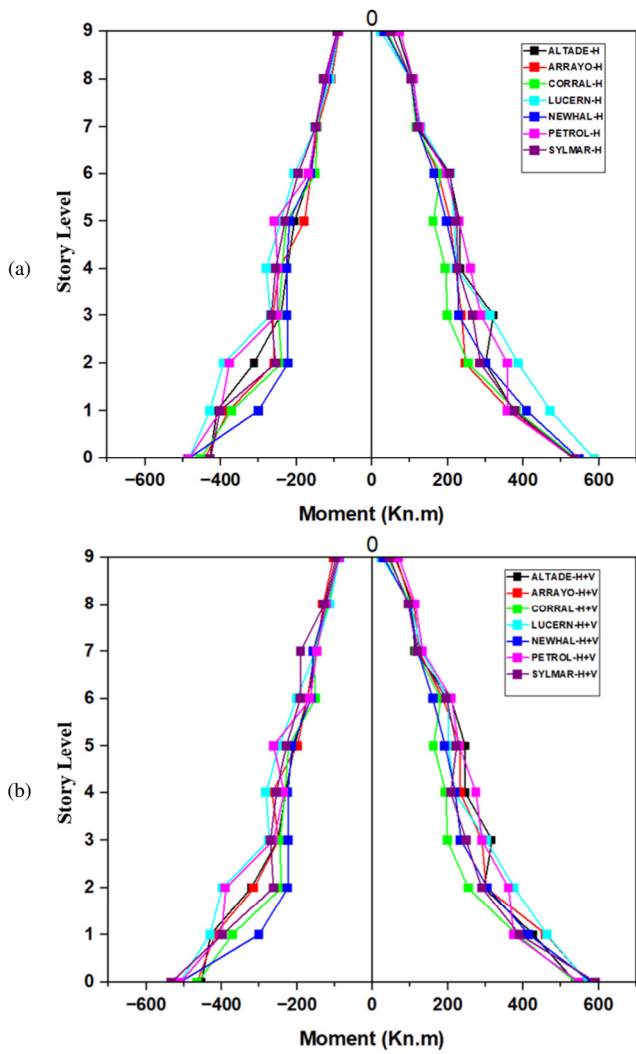


Fig. 6. Moment of the shore posts of a structure (a) under H and (b) H+V seismic loads for 2-story structure.

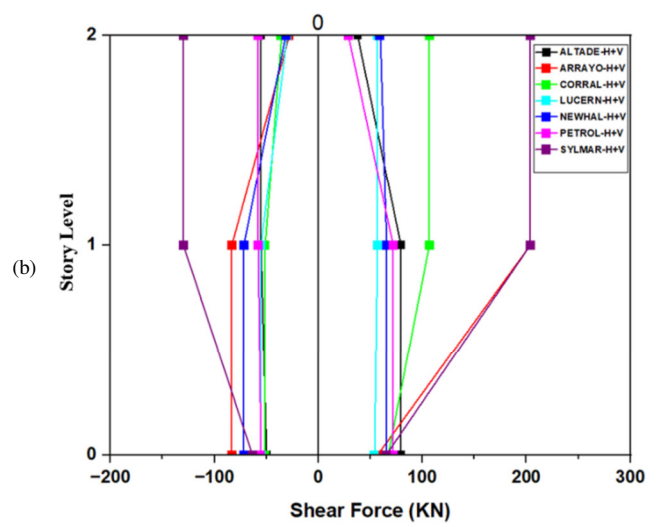


Fig. 7. Shear force of the shore posts of a structure (a) under H and (b) H+V seismic loads for 2-story structure.

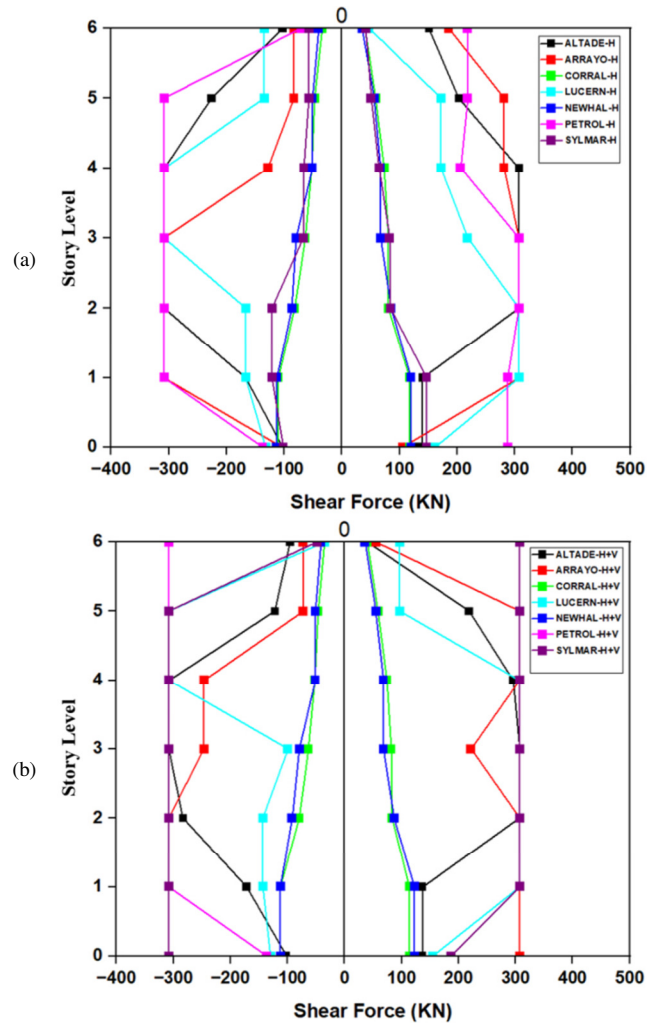
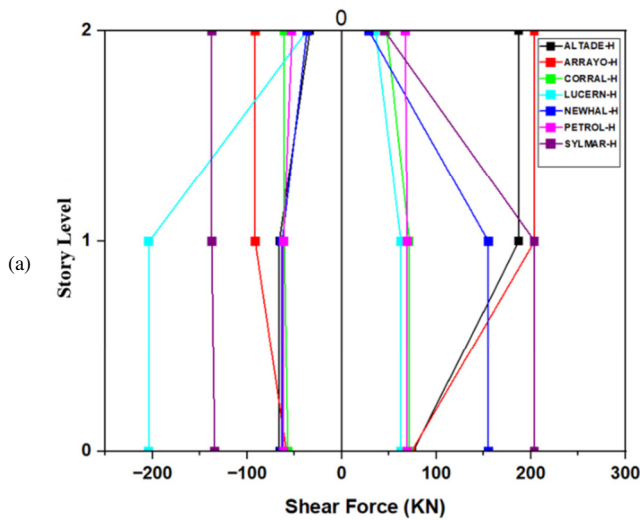


Fig. 8. Shear force of the shore posts of a structure (a) under H and (b) H+V seismic loads for 6-story structure.

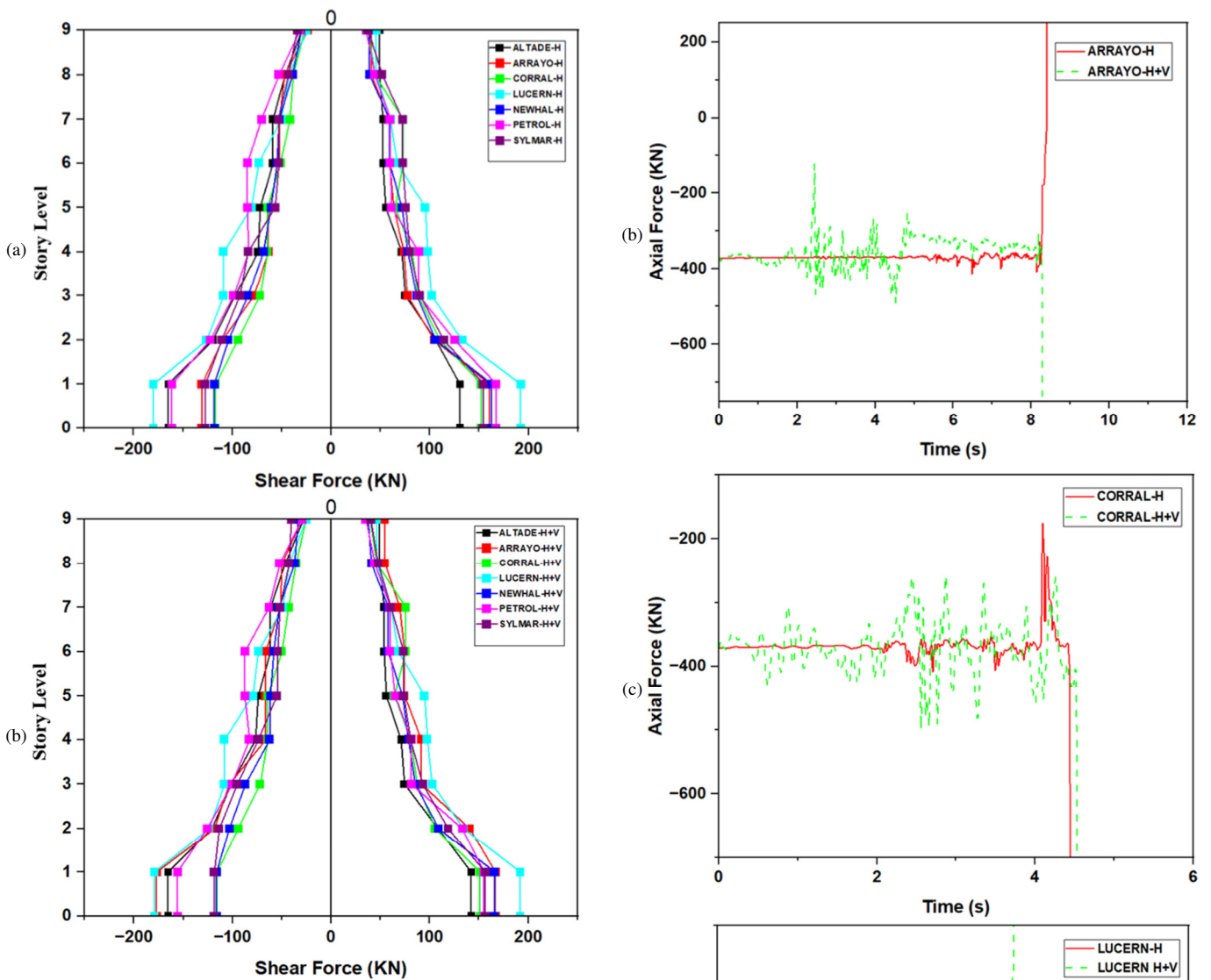
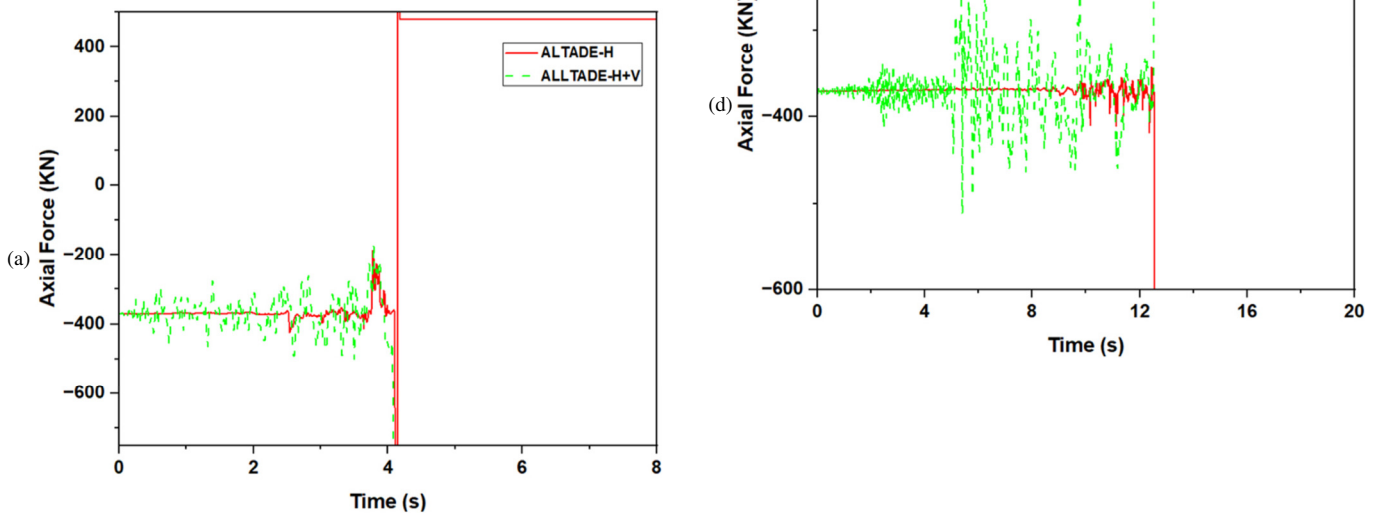


Fig. 9. Shear force of the shore posts of a structure (a) under H and (b) H+V seismic loads for 9-story structure.



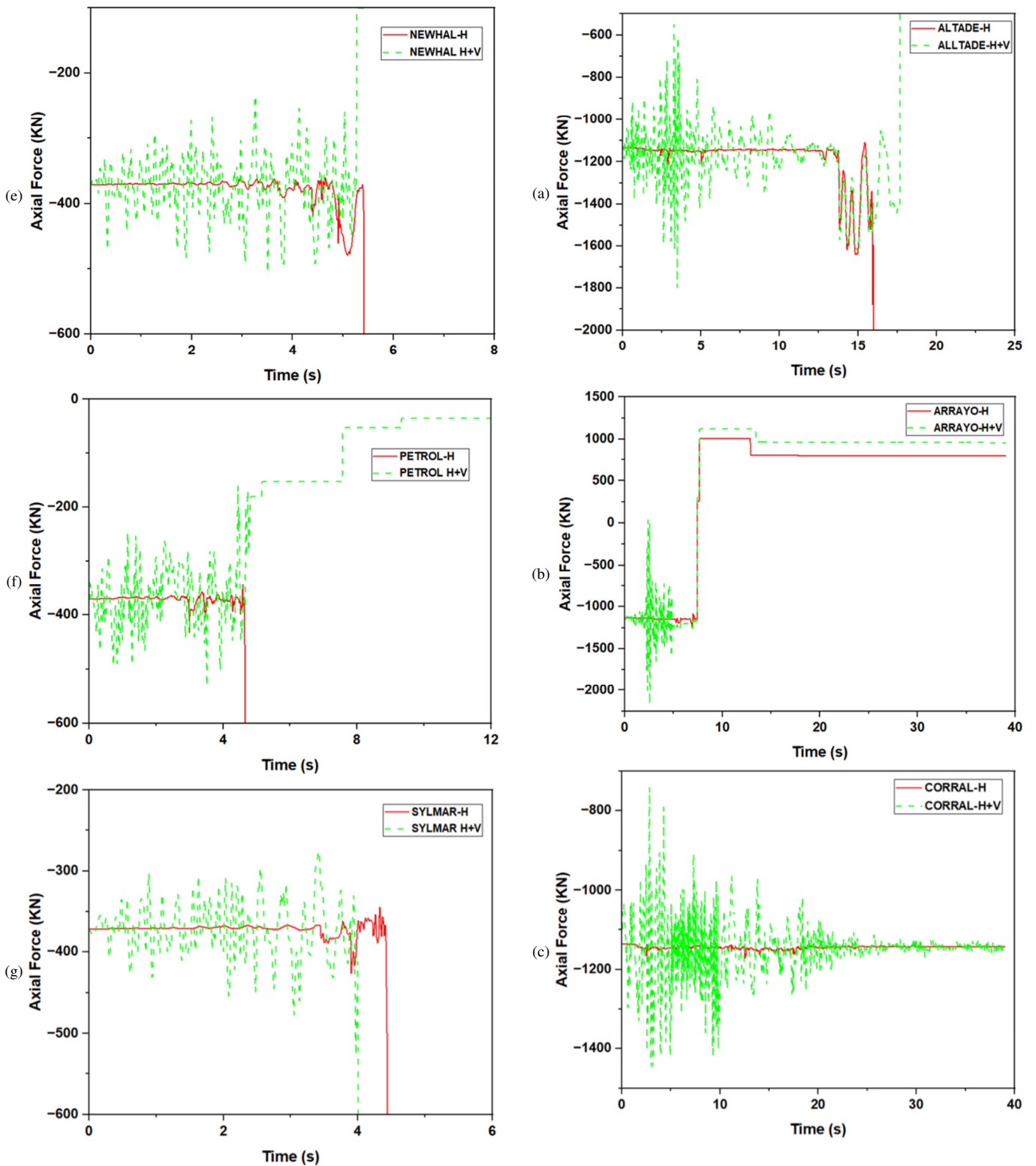


Fig. 10. Axial force of a central column of 2-story structure (a) under H and (b) H+V seismic loads for the: (a) Altade, (b) Arrayo, (c) Corral, (d) Lucern, (e) Newhal, (f) Petrol, and (g) Sylmar earthquakes.

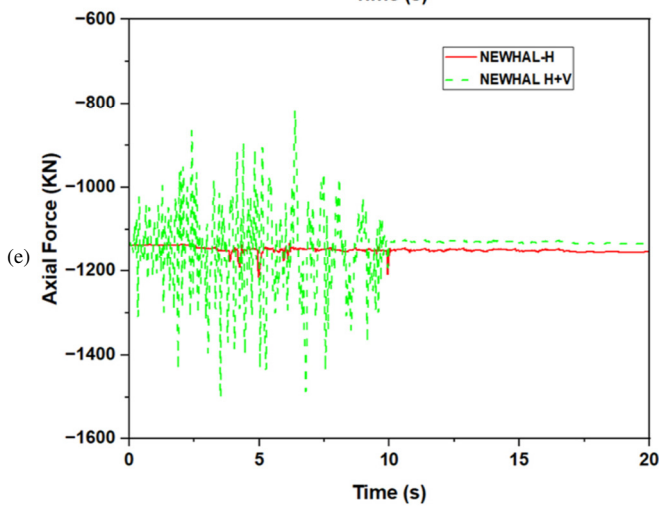
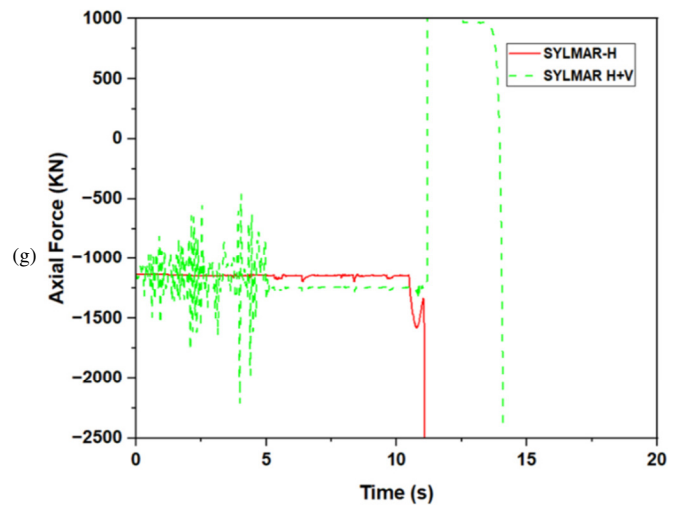
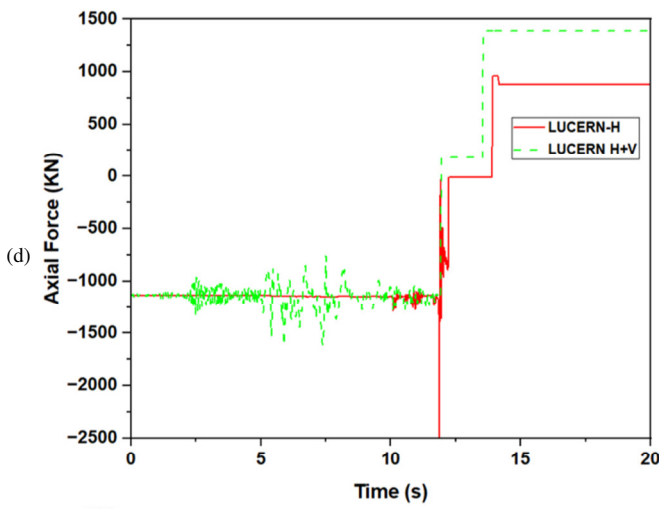
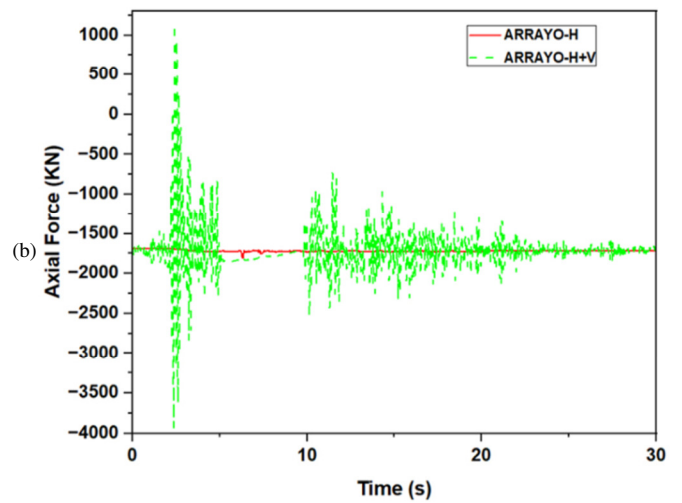
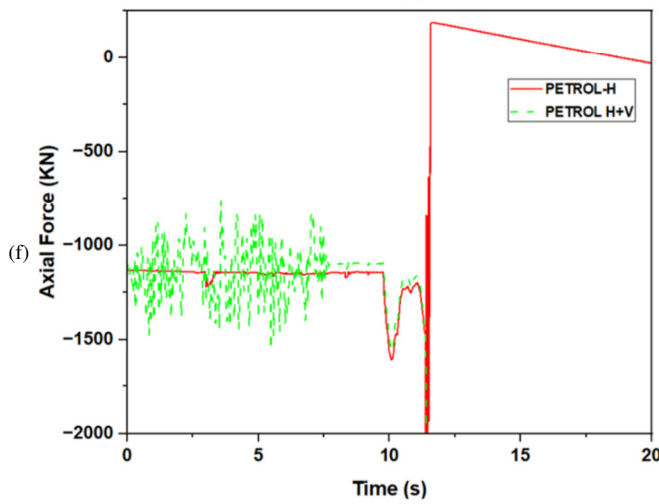
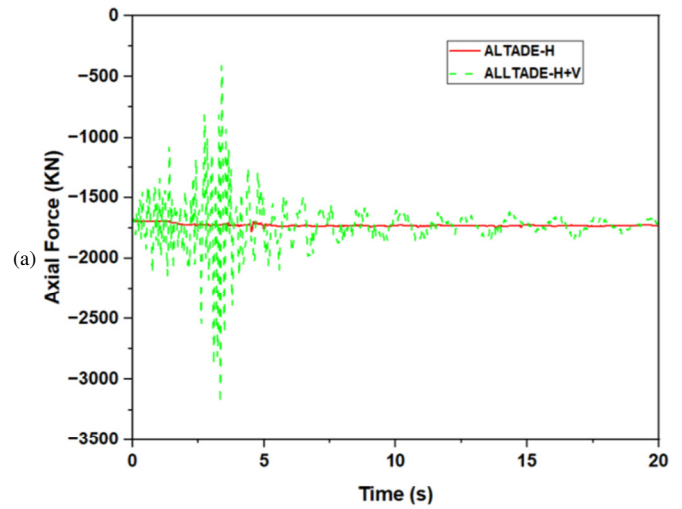


Fig. 11. Axial force of a central column of 6-story structure (a) under H and (b) H+V seismic loads for the: (a) Altade, (b) Arrayo, (c) Corral, (d) Lucern, (e) Newhal, (f) Petrol, and (g) Sylmar earthquakes.



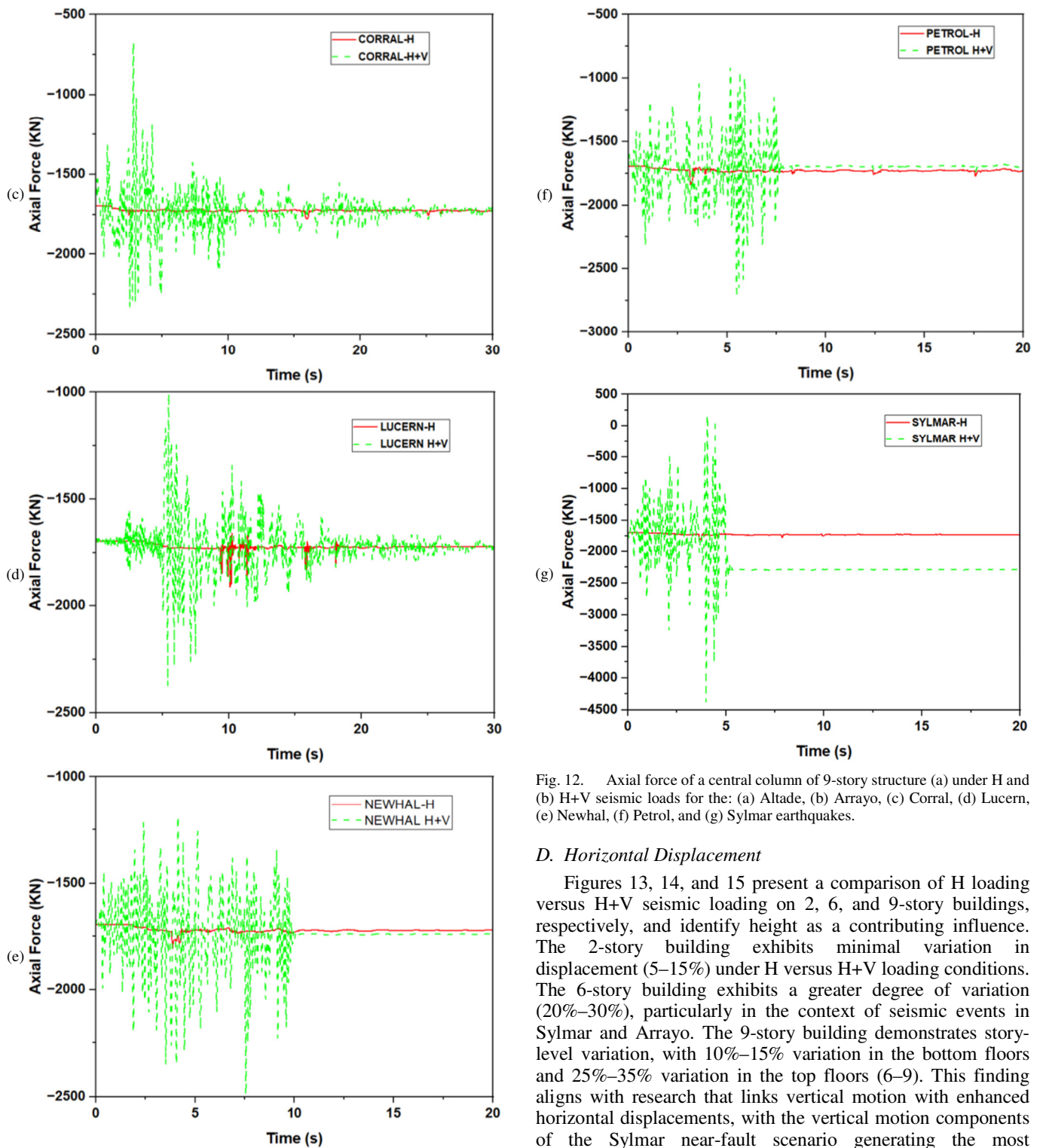


Fig. 12. Axial force of a central column of 9-story structure (a) under H and (b) H+V seismic loads for the: (a) Altade, (b) Arrayo, (c) Corral, (d) Lucern, (e) Newhal, (f) Petrol, and (g) Sylmar earthquakes.

*D. Horizontal Displacement*

Figures 13, 14, and 15 present a comparison of H loading versus H+V seismic loading on 2, 6, and 9-story buildings, respectively, and identify height as a contributing influence. The 2-story building exhibits minimal variation in displacement (5–15%) under H versus H+V loading conditions. The 6-story building exhibits a greater degree of variation (20%–30%), particularly in the context of seismic events in Sylmar and Arrayo. The 9-story building demonstrates story-level variation, with 10%–15% variation in the bottom floors and 25%–35% variation in the top floors (6–9). This finding aligns with research that links vertical motion with enhanced horizontal displacements, with the vertical motion components of the Sylmar near-fault scenario generating the most significant amplifications (30%–40%), while far-field Lucern exhibits the least variation (5%–15%). These findings support the hypothesis that the effects of vertical seismic activity increase with increasing height and are most pronounced in near-fault conditions of earthquakes.

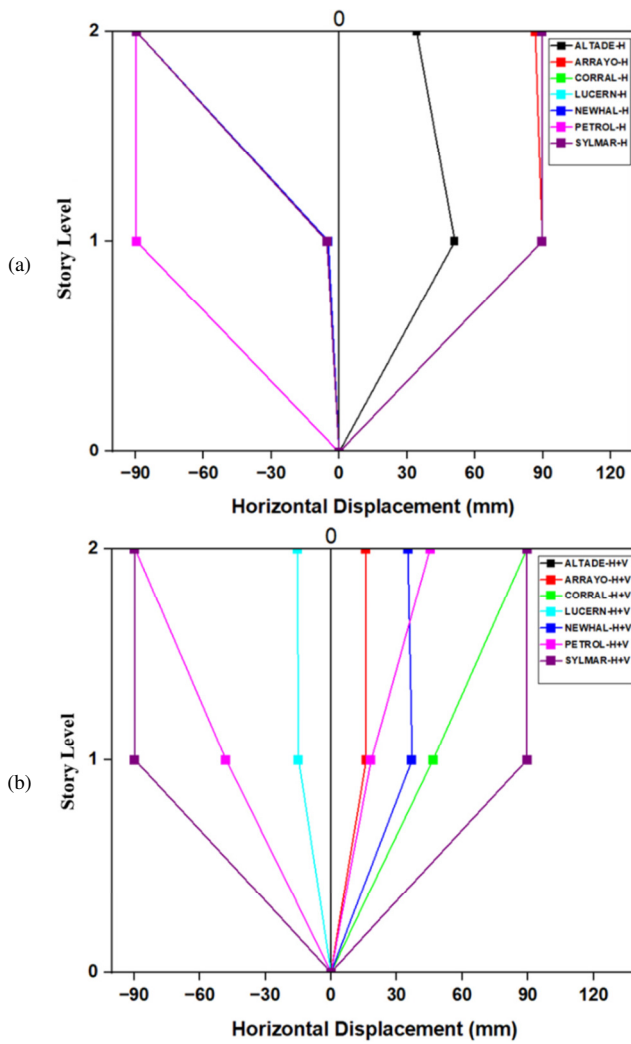


Fig. 13. Horizontal displacement of a 2-story structure (a) under H and (b) H+V seismic loads for the: (a) Altade, (b) Arrayo, (c) Corral, (d) Lucern, (e) Newhal, (f) Petrol, and (g) Sylmar earthquakes.

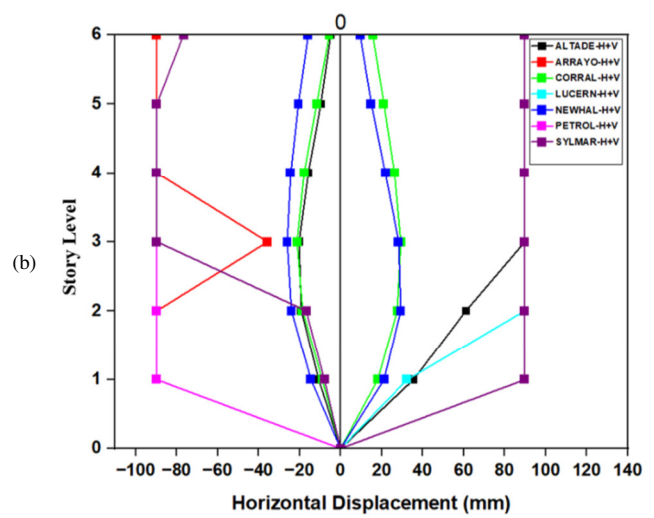
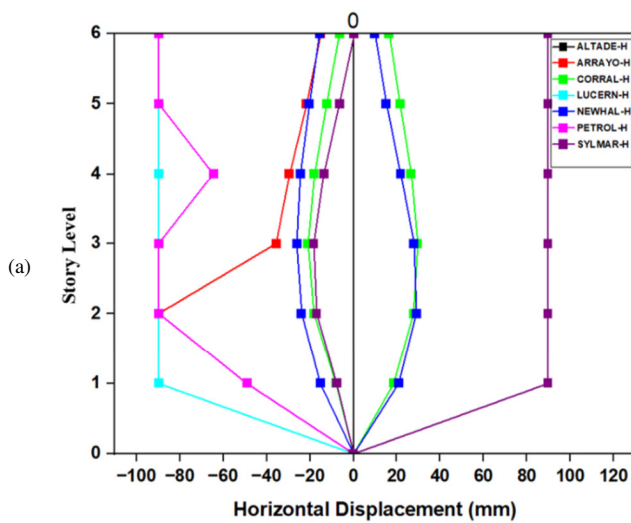


Fig. 14. Horizontal displacement of a 6-story structure (a) under H and (b) H+V seismic loads for the: (a) Altade, (b) Arrayo, (c) Corral, (d) Lucern, (e) Newhal, (f) Petrol, and (g) Sylmar earthquakes.

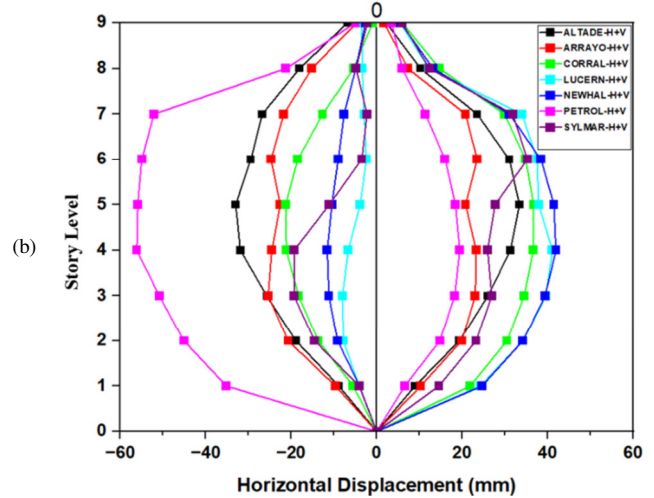
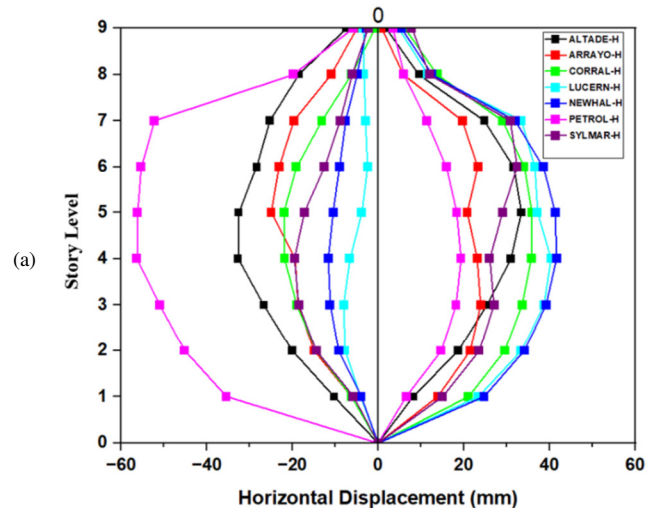


Fig. 15. Horizontal displacement of a 9-story structure (a) under H and (b) H+V seismic loads for the: (a) Altade, (b) Arrayo, (c) Corral, (d) Lucern, (e) Newhal, (f) Petrol, and (g) Sylmar earthquakes.

## V. CONCLUSIONS

The analysis of vertical seismic effects according to the Algerian code RPA 2024 reveals important information for seismic design, with a focus placed on building height in structural sensitivity. Low-rise buildings (2-story) show negligible effects from combined Horizontal and Vertical (H+V) loading with variations of 5% - 15%, and mid-rise buildings (6-story) show moderate effects (20% - 30%). In contrast, high-rise buildings (9-story) have significant height-dependent variations of 10-35%, especially in the higher stories (6-9), with displacements increasing by 25% - 35% under H+V loading. Patterns of internal force redistribution further demonstrate the complexity of vertical seismic action: moments vary by 15% - 50% between members, with peaks under Arrayo and Sylmar earthquakes (30% - 70%), and axial loads in central columns skyrocketing by 500% - 600% in 2-9 story buildings. Seismic record characteristics are critical and influence behavior, with near-fault records, such as Sylmar, inducing 30% - 40% larger displacements than far-field records, such as Lucern, which induce small variations of 5% - 15%. These observations underscore important design implications: horizontal-only analysis, as conventionally practiced, underestimates requirements, especially in taller buildings, and necessitates the incorporation of vertical components, as specified in RPA 2024. The observed behavior justifies the code's focus on combined H+V loading, especially in seismically active areas, and emphasizes the need for contemporary design practice to emphasize vertical seismic forces to improve structural resilience to dynamic and multidirectional seismic threats.

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