

SEISMIC DEMAND ON STEEL STORAGE PALLET RACKS LOCATED ON UPPER FLOORS

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Abstract

Steel storage pallet racks are a crucial component in logistics chains, industry, and customer goods supplies. Any direct affectation to steel storage pallet racks and their contents significantly diminishes society's recovery capacity and causes important economic losses. Due to these factors and considering the high seismic vulnerability of steel storage pallet racks observed during past earthquakes, it is crucial to understand their seismic response under different scenarios. Traditionally, steel storage pallet racks are placed on ground floors; hence, their seismic design considers the characteristics of ground motions. However, it is a common practice for retail and hardware stores in Colombia to have parking slots on the ground floors and commercial and storage areas on the upper floors. This configuration subjects steel storage pallet racks to floor motions rather than ground motions, leading to greater seismic demand at long periods that could correspond to those of the racks' down-aisle direction periods. This study compares the seismic demand, in terms of drifts and peak accelerations, on different configurations of steel storage pallet racks subjected to nonlinear analyses using ground and floor motion inputs.

Keywords: Steel storage pallet racks, seismic demand, seismic performance, nonstructural elements, nonlinear analysis.

1 INTRODUCTION

Colombia has experienced constant economic growth in the last decades, boosting the development of new industries and commerce. This growth requires the implementation of larger storage solutions for manufacturing, supply chains, and retail sales. In this regard, steel storage pallet racks are a common storage solution that allows fast load and unload procedures, as well as flexibility in their configurations. Steel storage pallet racks (Figure 1) are composed of specially designed cold-formed steel elements that enable easy installation and reconfiguration. Moment connection frames are typically used as structural systems in the longitudinal direction, whereas braced frames are typical for the transverse direction [1, 2]. The seismic response of these structures is highly variable. In traditional structures, such as buildings, live loads usually have the same order of magnitude as dead loads, while, in racks, the structural weight is very limited, generally not greater than 5% of the weight of the pallet units. Moreover, in the down-aisle direction, the great flexibility provided by connections and the absence of spine bracings reflect large periods of vibration (T), up to 3.50 s. Conversely, in the cross-aisle direction, the presence of bracing elements ensures periods of vibration shorter than 1.50 s. Despite their conventional lateral resistance schemes, the seismic response is governed by the hysteretic behavior of the base connections and brace-to-upright connections, where the inelastic deformations take place [3].

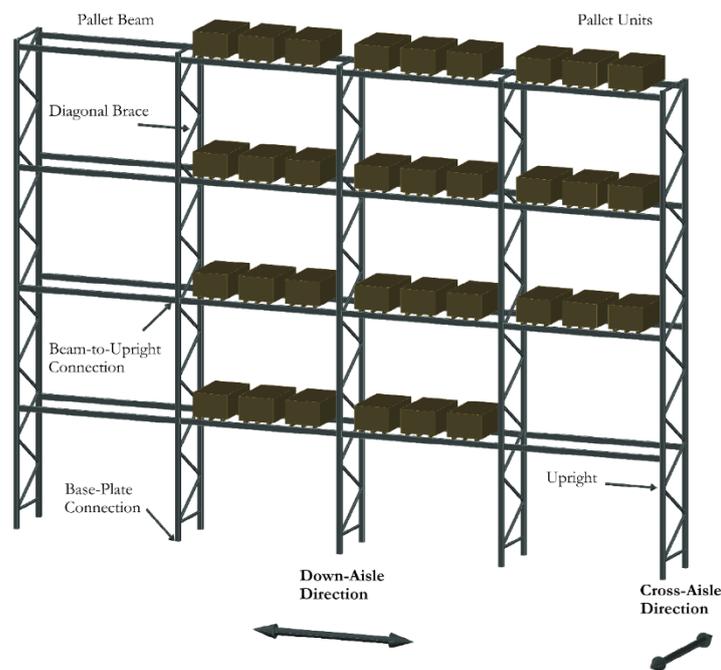


Figure 1 Typical configuration and main components of steel storage pallet racks.

Traditionally, steel storage pallet racks are located at ground level, therefore, their seismic input corresponds to the same ground shaking as other structures. However, to maximize area use, it is a common practice of department stores in Colombia to construct two- or three-story buildings in which the ground and first floors are dedicated for parking while the top floor is used for storage and commercial activities (Figure 2). This configuration completely changes the seismic demand on the steel storage pallet racks, which will be subjected to floor motions instead of ground motions.

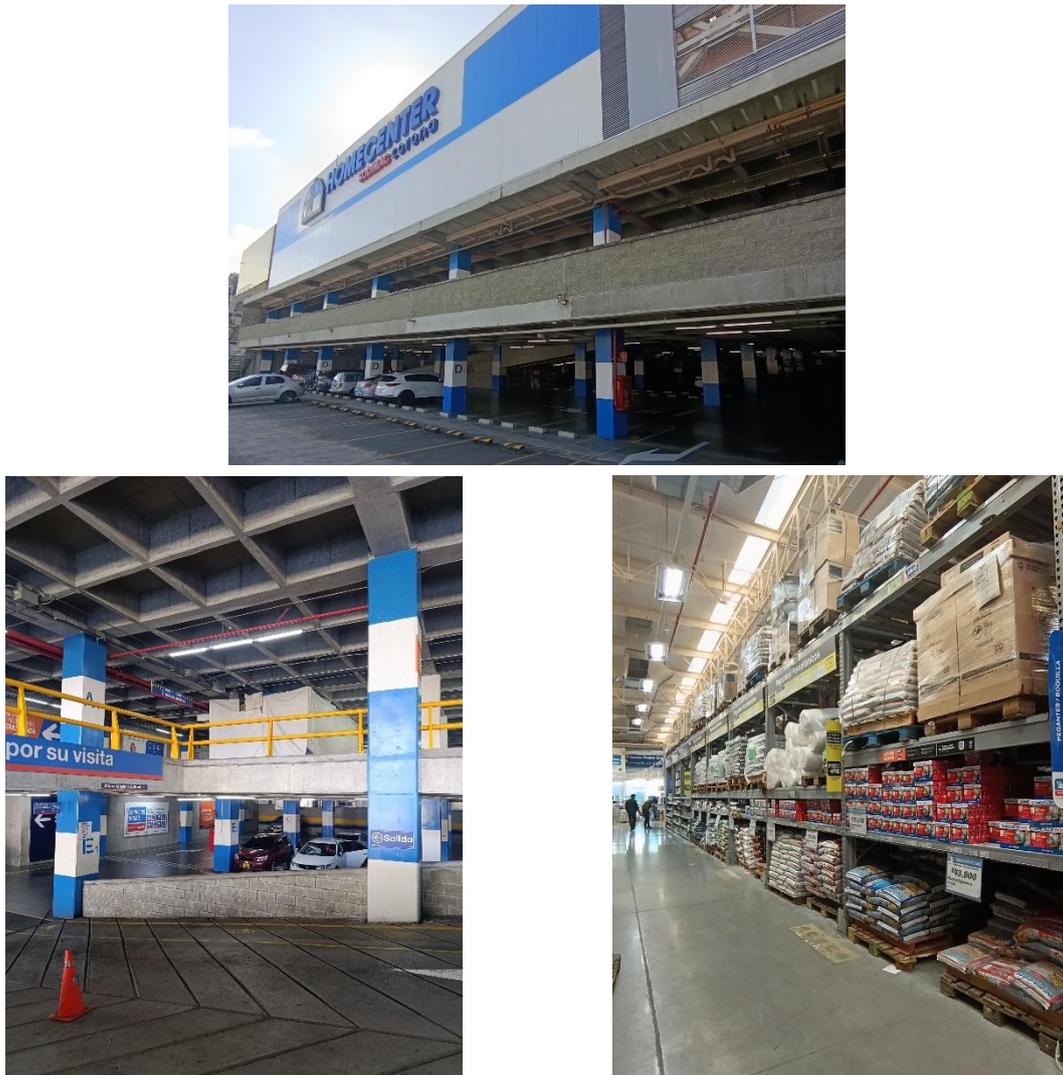


Figure 2 Example of a three-story retail store in Manizales, Colombia.

As explained by several authors [4-7], the structural system filters and amplifies the seismic input, changing significantly its frequency content and amplitude. Due to the high variability of the seismic response of steel storage pallet racks, it is important to assess their seismic behavior under floor motion inputs, typical of the Colombian implementation of such storage solutions.

2 CASE STUDY BUILDING AND SEISMIC HAZARD

2.1 Case study building

A case study building is proposed to assess the influence of floor amplification on the seismic demand for steel storage pallet racks. The case study building is a three-story reinforced concrete structure composed of three spans in the Y direction and five spans in the X direction, all of them with a length of 6.0 m. The ground floor and first floor correspond to the parking area and have a typical height of 3.0 m, while the top floor corresponds to the sales and storage area, where the racks are located, and has a height of 9.0 m. Figure 3 shows the typical plant view and an isometric view of the case study building. The concrete is characterized by a compression strength of 28 MPa and the rebars are assumed to have a yield strength of 420

MPa. The typical cross sections are equal to 0.75×0.90 m and 0.45×0.45 m for the columns and beams, respectively. The case study building was designed following the Colombian building code NSR-10 [8], assuming it was located in a high seismic area with soil type C, importance group II and vertical loads typical of those of parking areas and retail stores. Table 1 reports the longitudinal steel reinforcement quantities for the typical beams, whereas, for all the columns, this item was equal to 7106 mm^2 . The case study building is characterized by mode periods equal to 0.51, 0.49, and 0.44 s for the first three modes, reaching 90% of translational mode mass within the fifth mode. The case study building was modeled, including nonlinear properties, in ETABS v22.0. The structural elements were modeled using frame elements and the inelastic behavior was simulated through fiber sections characterized by concrete and steel rebar materials.

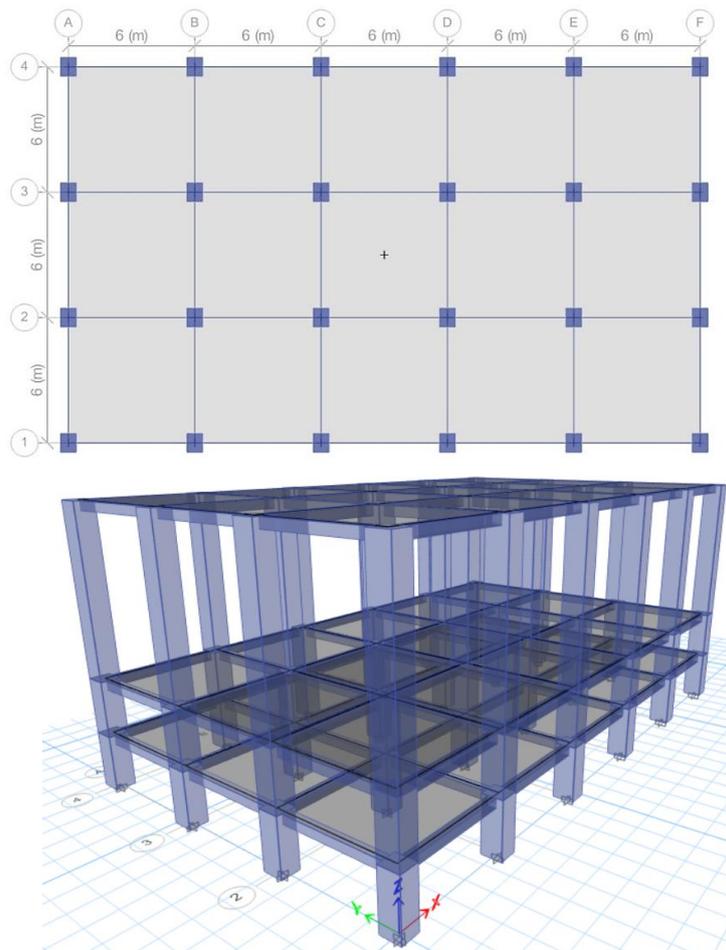


Figure 3 Plan view and isometric view of the case study building.

Table 1. Steel reinforcement quantities of beams
RC beam Longitudinal reinforcement (mm^2)

type	Top	Bottom
1	597	597
2	656	597
3	966	597
4	1342	767
5	1342	597

2.2 Seismic hazard

The site is assumed to be located in a high seismicity area by the Colombian building code [8] with a soil type C. Figure 4 shows the used design spectrum as per NSR-10. To obtain the floor motion records needed for the assessment of the steel storage pallet racks, a set of 11 ground motions was selected from the far-field ground motion set proposed in the FEMA P695 document [9] and scaled following the recommendations of the ASCE 7-22 [10] to match the design intensity. Figure 4 shows the average and envelope spectra of the scaled ground motions and the obtained floor motion records.

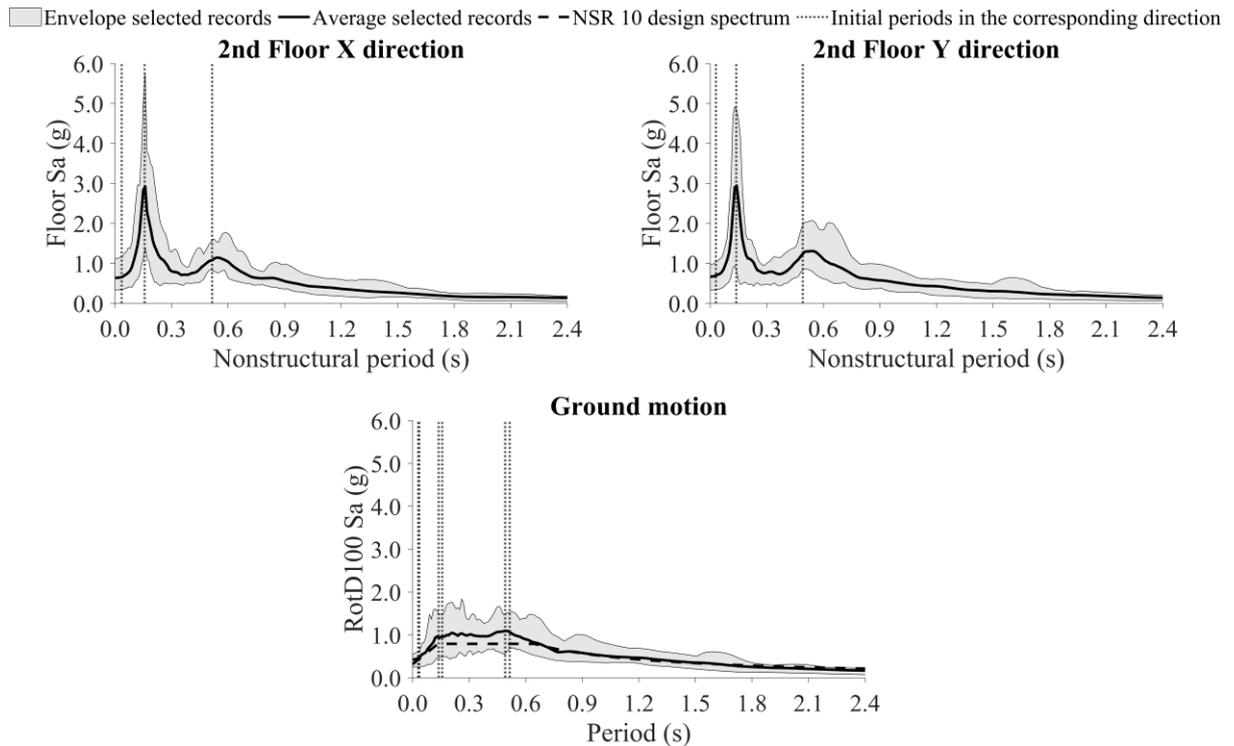


Figure 4 Seismic input 5% damping spectra and floor motion response 5% damping spectra.

3 CASE STUDY STEEL STORAGE PALLET RACK

The case study steel storage pallet rack was taken from the SEISRACKS2 project [11]. It has a down-aisle (longitudinal) length of 10.8 m divided into four bays, a cross-aisle (transversal) length equal to 1.1 m, and a total height of 8.2 m divided into four stories of 2.0 m each one plus 0.20 m at the top of the upright required for safety reasons. Figure 5(a) illustrates the case study steel rack. The structural system corresponds to a moment-resisting frame in the down-aisle direction and to a braced frame in the cross-aisle direction. In addition, the case study steel rack is composed of cold-formed steel elements with rectangular pipes (see Figure 5(b)) for the beams, omega sections for the uprights (see Figure 5(c)), and C sections for the bracing (see Figure 5(d)) elements. The case study steel storage pallet rack is characterized by fundamental periods in the down-aisle and cross-aisle directions equal to 2.25 s and 0.72 s, respectively. The yield strengths of the structural elements are equal to 420 MPa, 355 MPa, and 235 MPa for the uprights, beams, and braces, respectively. The pallet loads were simulated by applying a uniform lineal force equal to 4.3 kN/m in all the beams of the steel rack. The numerical model of the case study steel storage pallet rack was done using OpenSees [12]. The inelastic behavior of the beam-upright connection, as well as the buckling of the bracing

elements, were modeled using lumped plasticity at the end of elastic structural elements. Further details of the modeling assumptions can be found in [13].

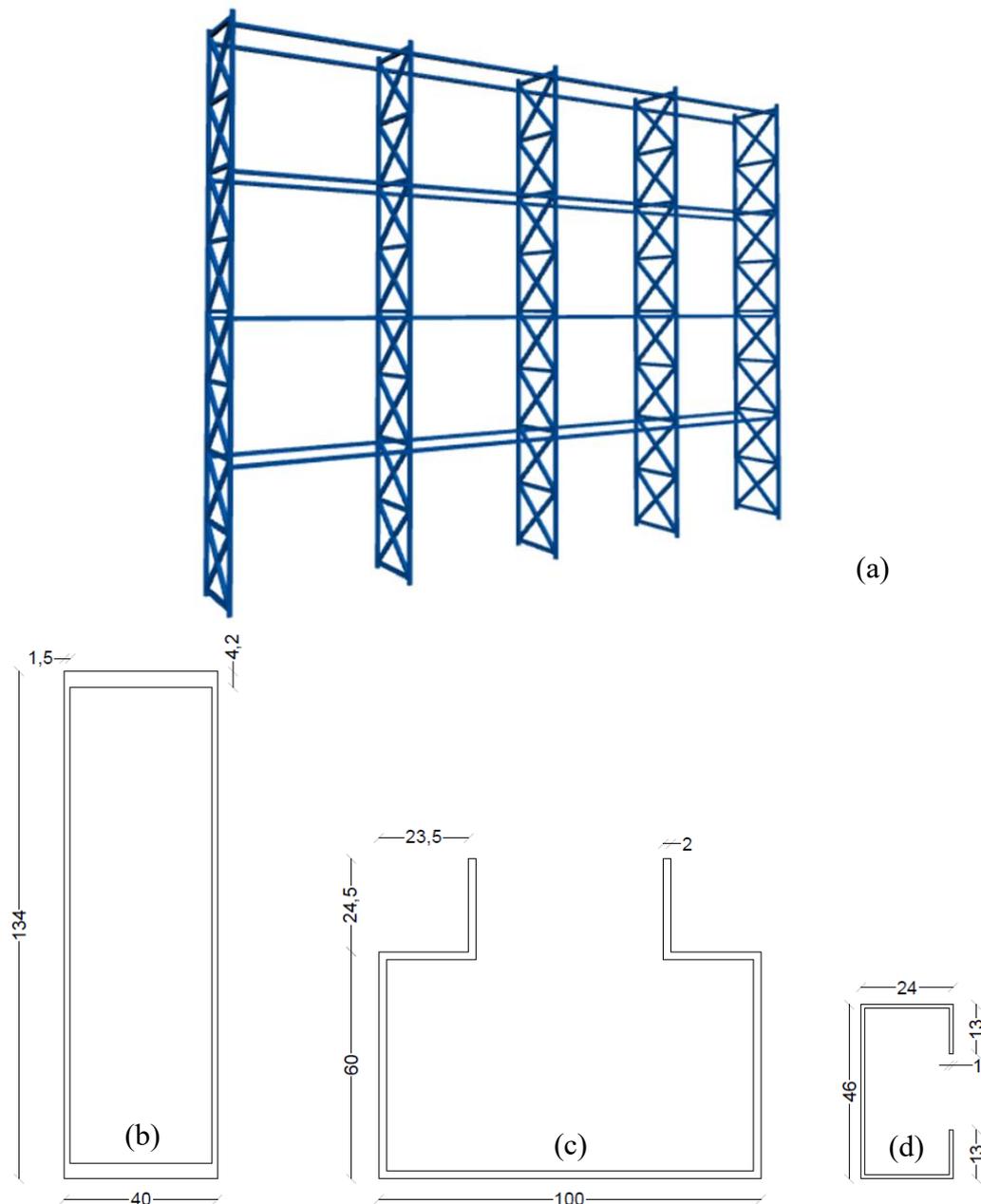


Figure 5 Case study steel storage pallet rack and the corresponding cross-sections (mm) of the structural elements.

4 NONLINEAR TIME-HISTORY ANALYSIS RESULTS

As explained before, 11 nonlinear time-history analyses were conducted on the case study building to obtain the respective floor motion. None of these ground motions induced the collapse of the case study building, however, most of them caused an inelastic response of the structure, especially in the top floor where a soft-story mechanism is formed due to the height difference. Then, the case study steel storage pallet rack was subjected to nonlinear time-history analyses using both the ground motions and the obtained floor motions. The seismic response

of the steel racks was assessed in terms of the probability of reaching life safety and collapse limit states, as well as story drifts, peak floor accelerations, and residual drifts of those records that did not cause the collapse of the steel rack. The life safety and collapse limit states are defined as any structural element that reaches the yielding strength and the failure strength, respectively.

The probability of reaching the life safety limit state is equal to 27.3% and 36.4% for the steel racks subjected to ground motions and floor motions, respectively. In addition, the probability of reaching the collapse limit state is equal to 9.1% for both seismic input conditions. Figures 6 to 8 show the median peak story drift, median residual drift, and median peak floor acceleration of the case study steel storage pallet rack subjected to the ground and floor motions. The results show that in general there was an increment in the seismic response of the case study steel storage pallet rack subjected to the floor motions compared to that of the case study rack subjected to ground motions. This increment is more significant in the cross-aisle direction than in the down-aisle direction, this could be caused by the amplification of high mode effects as high modes are closer to the spectral acceleration peaks observed in the floor motions. Specifically, there was an increment of 19% and 39% of the maximum median peak story drifts for the down-aisle and cross-aisle directions, respectively. In the case of the residual drifts, the case study rack subjected to the ground motions tended to show larger residual drifts in the down-aisle direction and lower residual drifts in the down-aisle direction than those exhibited by the case study rack subjected to the floor motions. The maximum differences were equal to 46% and 250% of the maximum median residual drifts for the down-aisle and cross-aisle directions, respectively. Finally, the median peak floor acceleration exhibited a maximum increment of 47% and 52% for the down-aisle and cross-aisle directions, respectively.

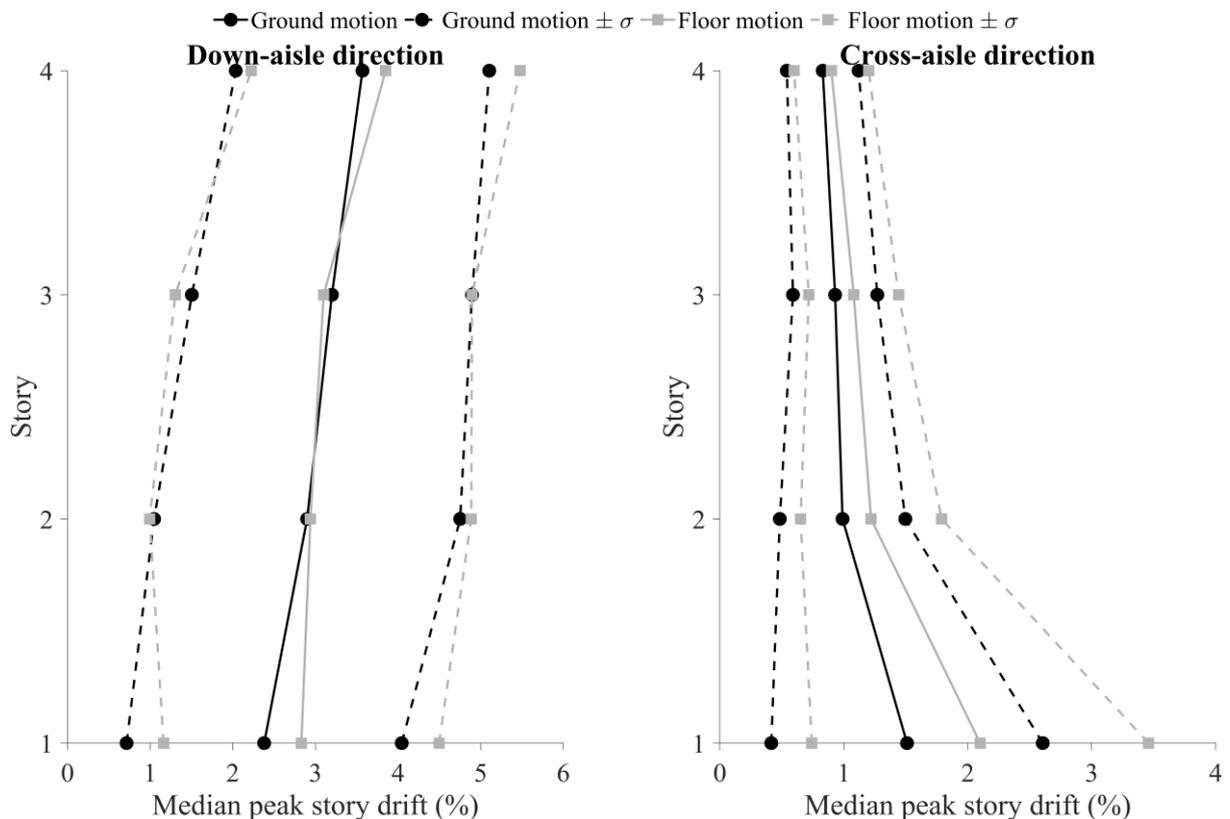


Figure 6 Median peak story drifts.

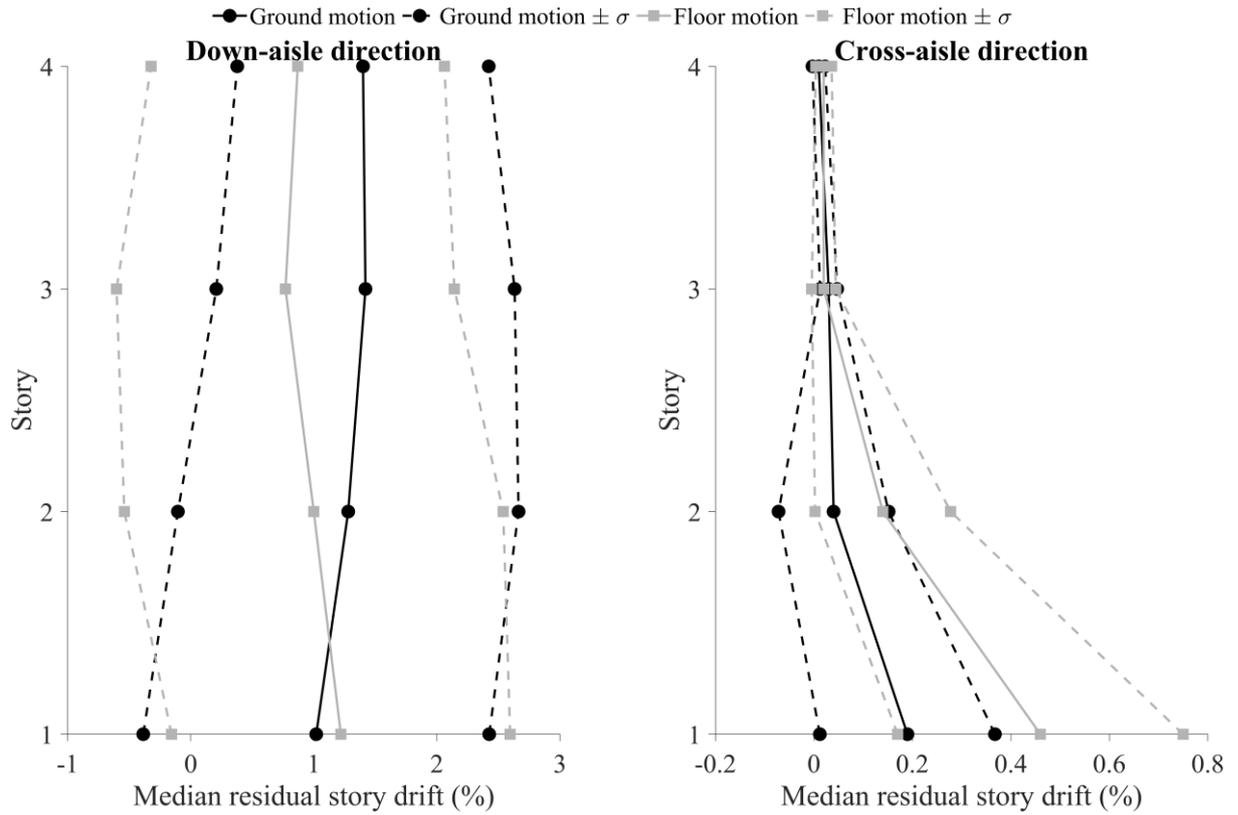


Figure 7 Median residual drifts.

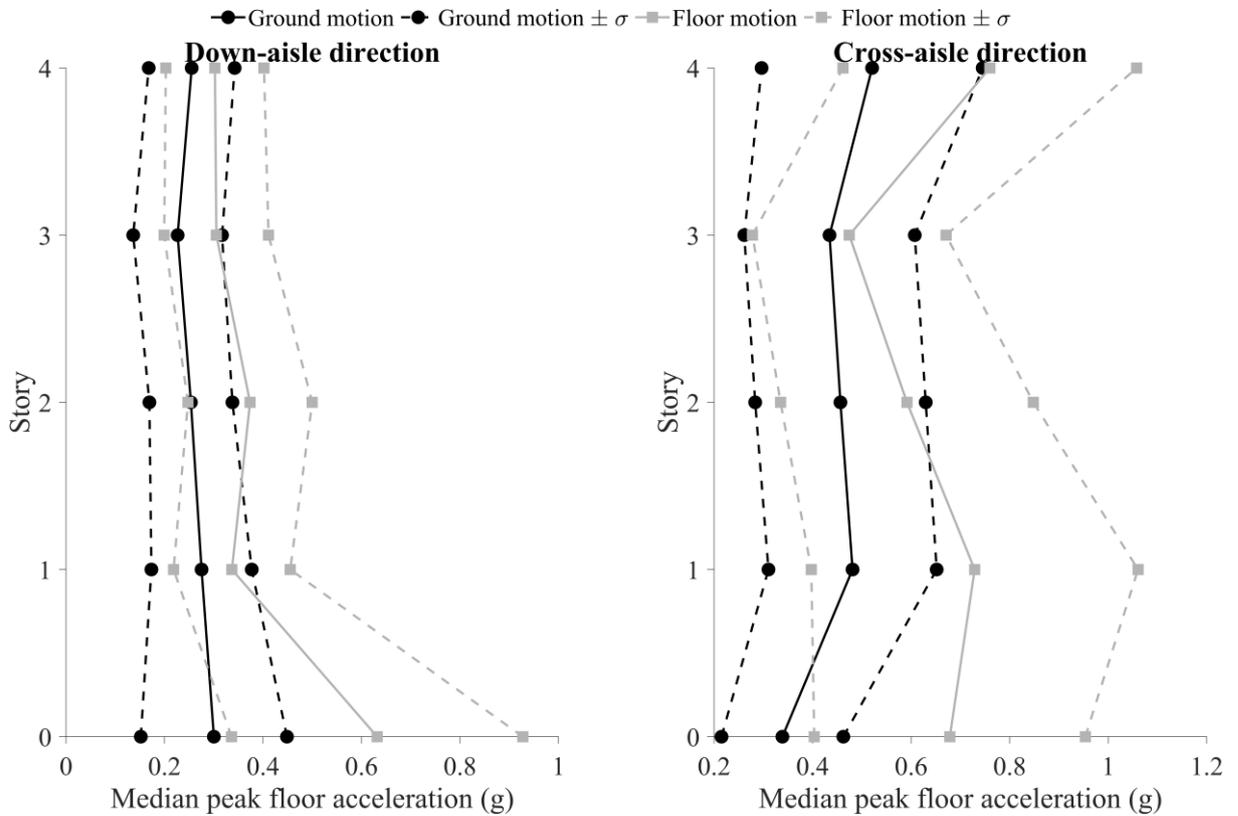


Figure 8 Median peak floor accelerations.

5 CONCLUSIONS

Traditionally, steel storage pallet racks are located on ground floors, therefore, for their seismic design, it is not considered any kind of dynamic amplification of the seismic input due to the seismic reaction of the building containing them. However, large retail and hardware stores in Colombia commonly have an architectural configuration in which the ground floor is used as a parking lot and the upper stories are used for commercial activities. This configuration implies the location of steel storage pallet racks on upper stories where the seismic input is modified, and usually amplified, by the dynamic response of the building. This study aimed to evaluate the seismic response of steel storage pallet racks located at upper stories. To fulfill this objective, a three-story case study building, representative of common retail and hardware stores in Colombia was designed and subjected to nonlinear time-history analysis to obtain floor motion records. These records were used as seismic input for nonlinear time-history analyses of a case study steel storage pallet rack, in addition, for comparison, the case study steel storage pallet rack was subjected to the ground motions for comparison. The seismic response of the case study steel rack was assessed in terms of the probability of reaching life safety and collapse limit states, as well as in terms of median peak story drifts, median residual drifts, and median peak floor accelerations. The results showed an increment in the seismic demand of the steel rack when subjected to floor motions, therefore, it highlights the need for accounting for dynamic amplification of the seismic demand on steel racks located at upper floors due to the building's seismic response. The specific conclusions are as follows:

- The probability of reaching the life safety limit state is equal to 27.3% and 36.4% for the steel racks subjected to ground motions and floor motions, respectively. In addition, the probability of reaching the collapse limit state is equal to 9.1% for both seismic input conditions.
- There was an increment of 19% and 39% of the maximum median peak story drifts for the down-aisle and cross-aisle directions, respectively, when the case study steel rack was subjected to floor motions.
- The case study rack subjected to the ground motions exhibited larger residual drifts in the down-aisle direction and lower residual drifts in the cross-aisle direction. The maximum differences were equal to 46% and 250% of the maximum median residual drifts for the down-aisle and cross-aisle directions, respectively.
- The median peak floor acceleration exhibited a maximum increment of 47% and 52% for the down-aisle and cross-aisle directions, respectively, when the case study rack was subjected to floor motions.

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REFERENCES

- [1] Pekoz, T., Winter, G., Cold-Formed Steel Construction, IABSE Periodica 1, 1980.
- [2] Godley, M.H.R. Design of cold formed steel members. Rhodes ed., 361-399, 1991.
- [3] Bernuzzi, C., Baldassino, N. Experimental analysis on the cyclic behaviour of beam-to-column joints in steel storage pallet racks. *Thin-walled Structures* 39, 841-859, 2001.
- [4] Merino, R.J., Perrone, D., Filiatrault, A. Consistent floor response spectra for performance-based seismic design of nonstructural elements. *Earthquake Engineering and Structural Dynamics* 49, 261–284. 2020.
- [5] Abo El Ezz, A., Assi, R., and Miralvand, T. Seismic Floor Acceleration Amplification Based on Instrumented Building Records. *Journal of Architectural Engineering*. 26. 2020.
- [6] Gabbianelli, G., Perrone, D., Brunesi, E., Monteiro, R. Seismic Acceleration and Displacement Demand Profiles of Non-Structural Elements in Hospital Buildings. *Buildings* 10, 243. 2020.
- [7] Kazantzi, A.K., Vamvatsikos, D., Miranda, E. Evaluation of Seismic Acceleration Demands on Building Nonstructural Elements. *Journal of Structural Engineering*. 146, 2020.
- [8] Asociación Colombiana de Ingeniería Sísmica. Reglamento Colombiano de Construcción Sismo Resistente NSR-10. 2010.
- [9] FEMA. Quantification of building seismic performance factors FEMA. United States: Federal Emergency Management Agency; 2009.
- [10] ASCE Minimum Design Loads and Associated Criteria for Buildings and Other Structures ASCE/SEI 7-22. 2021.
- [11] Commission of the European Union. Directorate General for Research and Innovation., 2014. Seismic behaviour of steel storage pallet racking systems (SEISRACKS2): final report. Publications Office.
- [12] McKenna F., Scott M., Fenves G.. Nonlinear finite element analysis software architecture using object composition. *Journal of Computing in Civil Engineering* 24(1). 2010.
- [13] Gabbianelli, G., Cavallieri, F., and Nascimbene, R. Seismic vulnerability assessment of steel storage pallet racks. *Ingegneria Sismica* 37(2):18-40.