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SEISMIC ASSESSMENT OF AN INNOVATIVE ENERGY DISSIPATION DEVICE FOR STEEL STORAGE PALLET RACKS

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Abstract

The European logistics industry, including warehousing, transhipment, and transport, is of vital importance to the European economy. The total European market for racking and storage equipment was yearly ca. € 4 billion in 2014 and has significantly increased in the last years. Steel storage pallet racks are a crucial component of this industry, which due to their structural characteristics (i.e., flexible connections and diaphragms, thin wall elements, and large stiffness difference between orthogonal directions), exhibit a high seismic vulnerability. To increase the energy dissipation capacity along the down-aisle direction, it is proposed a rotary hysteretic damper placed at the beam-to-upright connection, allowing adding supplemental damping without reducing the workable area of the steel storage pallet racks. The seismic assessment of the proposed device was carried out by subjecting different configurations of steel storage pallet racks to nonlinear time-history analyses. The seismic responses were measured in terms of fragility curves, peak drift and residual drift profiles and energy dissipation of beam-to-upright connections.

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

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1 INTRODUCTION

Steel storage racks are essential components in industrial warehouses and logistic facilities, playing a critical role in the supply chain by allowing vertical storage of goods. These structures are typically made of thin-walled cold-formed steel (CFS) profiles, optimized for vertical load resistance but highly sensitive to lateral actions, especially seismic ones. Past earthquakes [1] have shown that inadequately designed racks are prone to collapse, resulting in injuries, fatalities, and severe economic losses due to damaged goods and interrupted production.

Since the construction of the first industrial steel storage racks, within the supply chain that moves goods from producers to consumers, the main focus has undeniably been on the product itself, rather than on the structures responsible for supporting such valuable merchandise.

It is therefore necessary to highlight how, over the years, the issue of safety, particularly from a seismic perspective, has often been neglected when it comes to industrial steel storage racks in warehouses.

It is essential that their safety be ensured in all respects, not only against vertical loads but also, and above all, against horizontal forces, among which seismic action is certainly the most critical. In fact, when seismic events affect industrial racks, which are often not equipped with seismic protection systems, the risk of collapse becomes significantly high [2]. It is estimated that only a small portion of warehouses in Italy are built using techniques and solutions specifically designed to withstand seismic action.

It is important to emphasize that, for this type of structure, it is crucial to prevent localized damage in individual racks, as the collapse of a single unit can trigger the so-called “domino effect”, where the fall of one rack leads to the progressive collapse of others. Generally, this phenomenon is prevented performing experimental campaigns in order to characterize the rack sub-components [3-6].

The collapse of storage racks, on which goods are placed while awaiting delivery to consumers, can have serious and often tragic consequences, especially regarding the safety of workers operating within the same storage facility. Moreover, such collapses result in significant economic losses, both in terms of industrial operations and, above all, in the damage or loss of stored products [7].

Recent earthquakes, such as 1994 Northridge, California, 2010 and 2011 Christchurch, New Zealand, 2012 Emilia-Romagna, Italy and 2016 Kumamoto (Japan), have affected steel storage structures. These events have caused major losses, not only economically but sadly also in terms of human lives among those present in the warehouses.

These failures emphasize the need for dedicated seismic design criteria and dissipative solutions tailored to the specific behaviour of storage racks. This study investigates a friction-based seismic protection strategy for steel storage racks, focusing on improving their seismic performance. A friction device is introduced at the beam-to-upright connections to enhance energy dissipation. The effectiveness of this solution is evaluated through nonlinear dynamic analysis using the Multiple Stripe Analysis (MSA) method.

2 CASE STUDY DESCRIPTION

2.1 Steel storage pallet rack

The rack investigated, namely IPA, in this paper is one of the structures considered within the framework of the research project SEISRACKS2 [8], funded by the Research Fund for Coal and Steel of the European Community.

The pallet rack under examination has a total longitudinal length of 10.8 meters, as it consists of four bays, each measuring 2.7 meters in length.

In height, the rack extends for 8.2 meters and is composed of four levels, each with an inter-level height of 2 meters. The uprights extend an additional 20 cm at the top, serving both logistic and safety functions.

Unlike the longitudinal direction, where, as will be shown later, the upright-to-beam connections are equipped with a friction-based seismic device, the transverse direction is braced with diagonal and horizontal elements. This bracing enhances the stiffness of the structure, which is inherently vulnerable when subjected to seismic events.

In accordance with what has been previously stated, the racking system is composed of members made of thin-walled steel profiles.

The vertical uprights and bracing elements have a C-shaped cross-section, while the horizontal beams have a rectangular shape. Figure 1 illustrates the cross-sectional shapes and their corresponding geometric dimensions, expressed in millimetres.

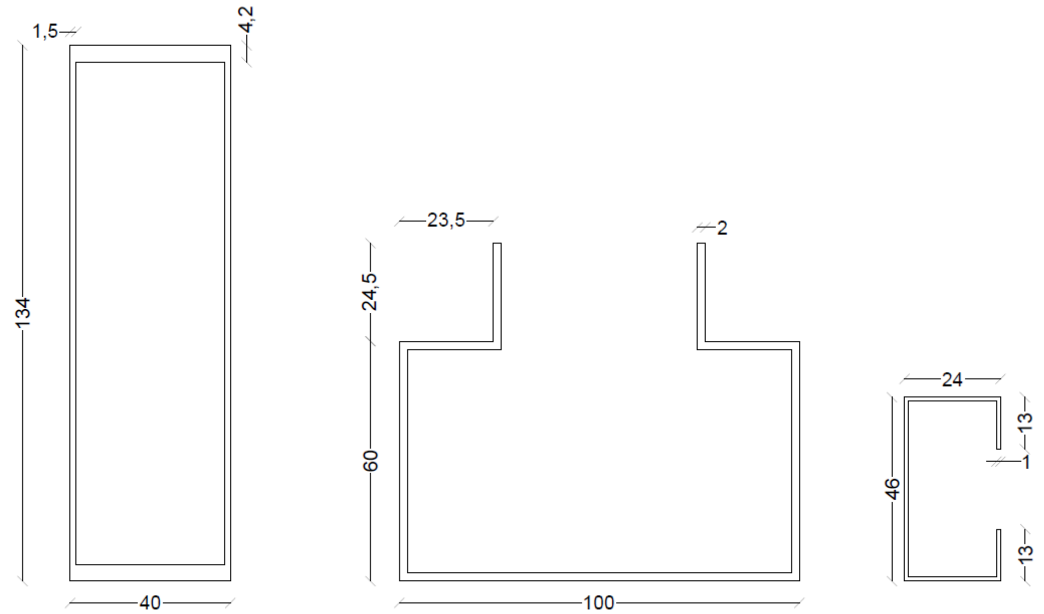

Figure 1 Upright, beam and brace section adopted for the case study.

Regarding the connection's behaviour, the hysteresis shape was obtained by SEISRACKS2 [8]; however, the project provides the curve in non-dimensional form; hence the assumption of scaling the maximum moment of the connection with respect to the 80% and 20% of the upright and beam sections was adopted, respectively.

2.2 Anti-seismic dissipative device

As already discussed, the design of industrial steel racking systems before 2000 has historically not accounted for seismic resistance, making these structures vulnerable to horizontal seismic actions.

As a result, even under seismic events with relatively low demand, these vulnerable systems are prone to reaching a state of global instability, often leading to incipient collapse. This, in turn, causes significant economic losses for the owners due to the destruction of goods stored on the racks.

Within this context, several seismic protection strategies were developed [9-11]. In this work, a novel friction-based seismic device, is proposed that is applied exclusively at the upright-to-beam connections. The device is designed to increase the energy dissipation, thereby preserving the overall stability of the structure.

Moreover, once the seismic event has occurred, the device can be replaced with a new one, thus allowing the racking system to be restored and made ready to withstand future seismic events. In this case, i.e. for existing storage racks, it would be important to fulfil a dynamic characterization, as highlighted in several works for racks [12], [13] and traditional structures [14-17], in order to estimate the level of damage reached.

The device is composed of steel plates that slide, featuring a rotational behaviour; the rotation generates friction, which in turn results in energy dissipation, a key mechanism for seismic protection.

Depending on the amount of torque applied to the bolts of the device, expressed in terms of preload force, a corresponding activation moment is generated, which is influenced by the resistance characteristics of the upright and beam.

As long as the seismic demand remains below the friction force threshold, no sliding occurs in the seismic device, and its behaviour can be considered rigid.

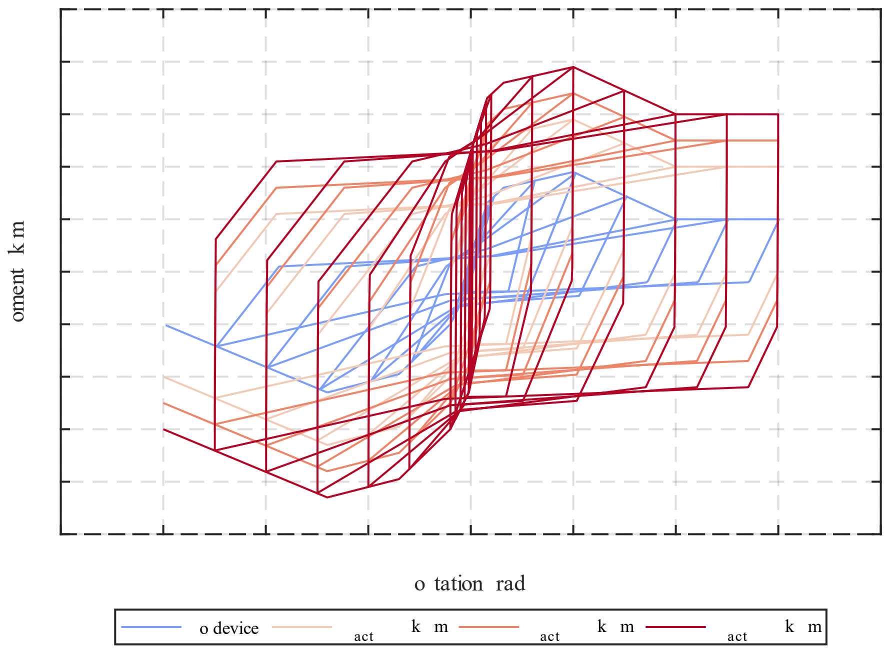

Figure 2 Moment-rotation behaviour of the beam-to-column connection, both without and with the device, considering different activation moments.

However, once this friction force is overcome, i.e., when the activation force defined by the bolt preload is exceeded, the device begins to slide, and this movement enables energy dissipation.

At this point, the device exhibits an indefinitely plastic behaviour, characterized by a wide hysteresis loop that reflects the amount of energy dissipated during the entire seismic event.

As shown in Equation 1, the total resistance of the beam-to-upright connection (M_T) is defined as the sum of the inherent connection resistance (M_{btc}) and the activation moment of the device (M_{act}).

$$M_T = M_{btc} + M_{act} \tag{1}$$

It is important, in the designing phase of the activation moment of the device, to not exceed the total resistance of the connection to the bending capacity of the beam in order to avoid beam failure.

The nonlinear behaviour of the connection is modelled through the UniaxialMaterial Pinching4 provided by OpenSeesPy [18], while the UniaxialMaterial ElasticPP is used to represent the perfectly plastic behaviour of the friction device.

These two different responses are combined within the same upright-to-beam connection using a simplified assumption: the seismic device and the beam-to-column connection are modelled as two springs acting in parallel. In this way, the resulting hysteresis loop is initially rigid up to the activation force; beyond this threshold, the seismic device comes into play. By sliding through friction, it enables the dissipation of energy generated by the seismic event.

With the aims of performing parametric study and identifying the best configuration of the device, different activation moments were tested, adopting 0.5 kNm, 1.0 kNm, 1.5 kNm and 2.0 kNm.

More specifically, the seismic response of the IPA racking system associated with each of these values will be compared to the case where no such device is present, in order to highlight the differences between the two scenarios.

Figure 2 illustrates the numerical calibrations corresponding to the different values assigned to the activation moment of the seismic device.

As shown, a direct consequence of increasing this value is the enhancement of the resistance offered by the beam-to-column connection, expressed in terms of greater energy dissipation and, consequently, a larger area enclosed by the hysteresis loop.

2.3 **Seismic hazard**

The seismic hazard was characterized for the site Pavia di Udine, Italy, a high seismicity zone. Ten return periods were considered (30 to 9975 years) with the Average Spectral Acceleration (AvgSa) as intensity measure. This allowed the execution of the Multiple Stripe Analysis (MSA), a methodology based on nonlinear dynamic analyses used to describe, through fragility curves, the seismic vulnerability of the examined rack systems.

More specifically, each return period was associated with a different set of natural accelerograms. For this case study, 20 records were selected per return period, accounting for the variability of ground motions. To fulfil this task, the algorithm of Ozsarac et al. [19] was adopted.

In this way, unlike what happens in Incremental Dynamic Analysis (IDA), excessive scaling of the accelerograms is avoided, thus preserving their frequency content since each return period is matched with a different set of compatible records.

To select ground motions generated by earthquakes consistent with the seismic hazard at the site under consideration, a Probabilistic Seismic Hazard Analysis (PSHA) was carried out. This analysis made it possible to identify the seismotectonic characteristics of the site, such as moment magnitude (M_w), epicentral distance (km), and standard deviation (ε)

The Multiple Stripe Analysis was carried out using the Average Spectral Acceleration (AvgSa) as the intensity measure (IM) of the ground motion. Within a predefined period range, AvgSa allows the conditioning of ground motion spectra so that they exhibit similarity in terms of spectral amplification.

The bounds of this interval depend on the fundamental vibration period of the storage rack, as obtained from modal analysis. For this case study, without the device, the period (T_1) is equal to 2.25 seconds.

In accordance with the formulation proposed by Kohrangi et al. [20], the reference period range for AvgSa is defined between $0.1 \cdot T_1$ and $1.5 \cdot T_1$. This formulation is generally applicable in the context of residential buildings, where the structures tend to be stiff and, therefore, exhibit relatively low vibration periods.

In the present case study, the structure is more flexible and thus associated with a higher fundamental period. Following the original formulation would result in a reference range that essentially spans the entire response spectrum. Therefore, a more accurate definition of the interval bounds is required.

In particular, since the analysis accounts for material nonlinearities, the structure undergoes damage, resulting in stiffness degradation and, consequently, an elongation of the fundamental period.

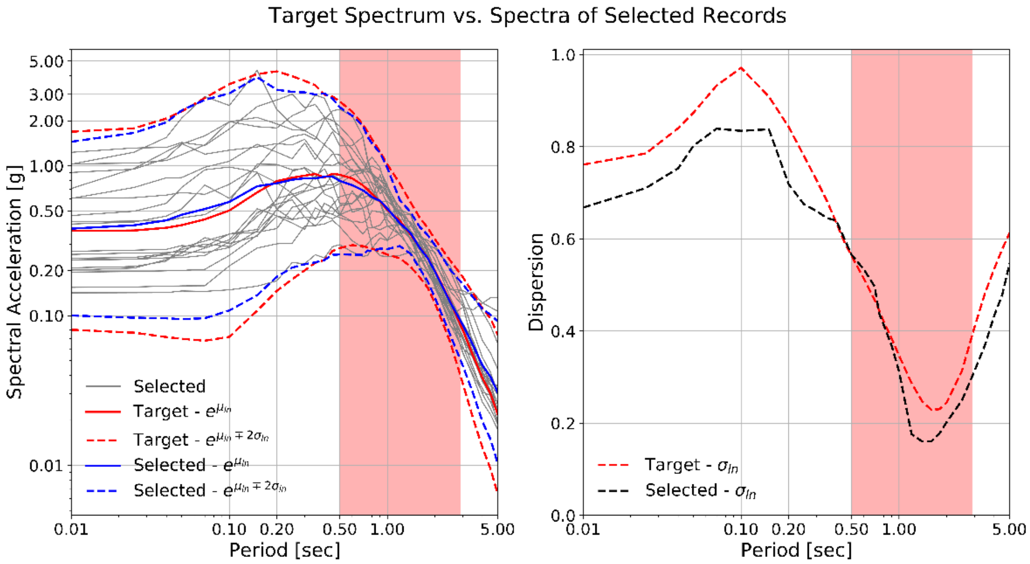

Figure 3 Record selection for a specific return period. The pink area represents the interval adopted for the Average Spectral Acceleration.

To consider this effect, the upper bound of the AvgSa interval is set higher than the fundamental period but lower than the value obtained from the original formula: $T_{up} = 3.0$ s.

The lower bound is chosen to account for the influence of higher vibration modes. However, in this case study, a significant portion of the participating mass is already mobilized in the first vibration mode (up to 85%). Nonetheless, the lower bound is assumed to be higher than that derived from the original formula: $T_{lw} = 0.5$ s.

An example of the selection of 20 natural accelerograms for a return period is shown in Figure 3. As can be seen, within the AvgSa reference range (highlighted in pink), the selected records show low variability in terms of spectral amplification.

3 NONLINEAR TIME-HISTORY ANALYSIS RESULTS

As previously stated, for each of the ten considered seismic return periods, a set of 20 natural accelerograms was selected and applied to the base nodes of the racking system along both horizontal directions.

The equivalent viscous damping adopted in the analyses is assumed to be 10%. Although this value is relatively high compared to what has been observed in past experimental studies, it was chosen because, as also highlighted in the seismic rack standards [21], the sliding of the pallets on the racks contributes to reducing the seismic demand, acting as a tuned-mass damper.

It is also noted that five different models were developed to represent the racking system. The variation among them lies in the value of the activation moment of the friction-based seismic device located within the upright-to-beam connections.

The focus of the discussion lies in the discrepancies between the model without the seismic device and those that, thanks to its inclusion, exhibit reduced seismic vulnerability.

Specifically, the results are presented in terms of fragility curves, interstory drift profiles, and energy dissipated by the connections during the seismic event.

3.1 **Fragility curves**

As mentioned, one of the outcomes derived from the execution of the Multiple Stripe Analysis (MSA) is represented by the fragility curves, which allow for the assessment of the seismic vulnerability of the racks.

These graphs plot the AvgSa as the Intensity Measure on the x-axis, and the probability of exceedance of the specific Limit State on the y-axis.

More specifically, for each of the ten seismic return periods considered, damage indicators, commonly referred to as Engineering Demand Parameters (EDPs), are defined. These are engineering parameters whose exceedance indicates that a specific Limit State has been reached by the structure. The EDPs considered, in accordance with the current design codes, include: shear and tensile capacity limits of the base plate anchoring the upright to the floor, the onset of local instability or yielding of bracing elements, reaching the yielding stress in beams and uprights, and the attainment of the ultimate rotation of the connections, corresponding to the rotation associated with the maximum strength in the nonlinear behaviour of the connections or bracings.

For each seismic return period, the number of times the thresholds imposed by the EDPs are exceeded is computed, allowing for the estimation of the corresponding probability of occurrence.

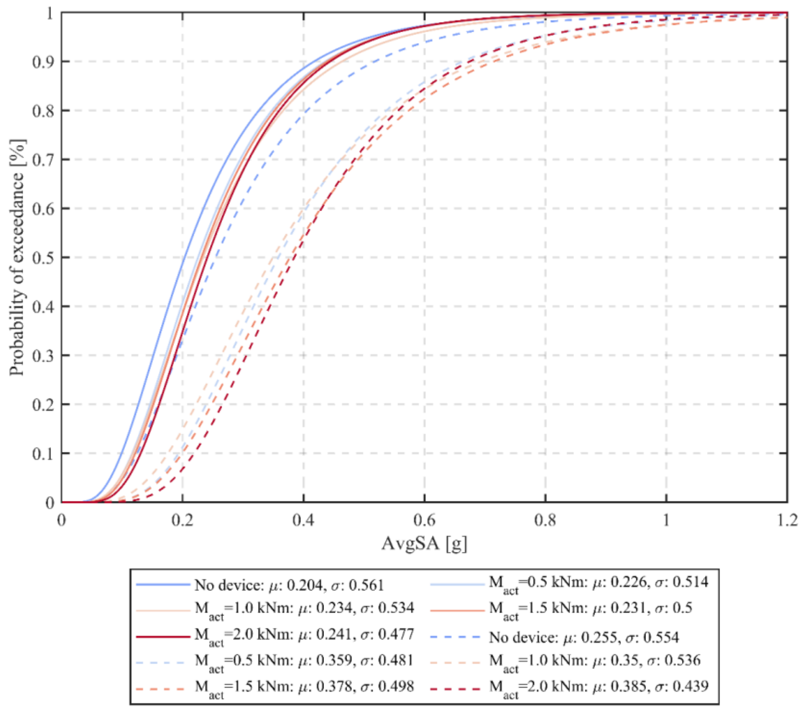

Figure 4 Fragility curves for Life Safety and Collapse limit states.

As the return period of the seismic event increases, the frequency with which the Limit State is reached also increases, and therefore, so does the probability.

The lognormal curve that fits the data points representing the probability of occurrence of a given Limit State, using the Maximum Likelihood Estimation (MLE) method, is the fragility curve. Figure 4 shows the fragility curves associated with the Life Safety (LS) limit state, represented by solid lines, and the Collapse (C) limit state, represented by dashed lines.

As can be seen, for both limit states, the racking system equipped with seismic devices at the connections exhibits lower seismic vulnerability compared to the standard structure.

More specifically, this reduction is greater for higher values of the activation moment of the device.

In particular, it is worth noting that for the Collapse limit state (C), the inclusion of this dissipative solution leads to an improvement in the seismic performance of the racking system: there is, in fact, a gain of 0.13g in the Intensity Measure that the structure can withstand before the defined EDPs reach the 50% of probability of exceeding.

3.2 Interstory drift and residual interstory drift

The following section presents some of the results related to the interstory drifts and residual interstorey drift of the racks, which serve as key parameters for assessing the deformability and, consequently, the stiffness of the steel racking system.

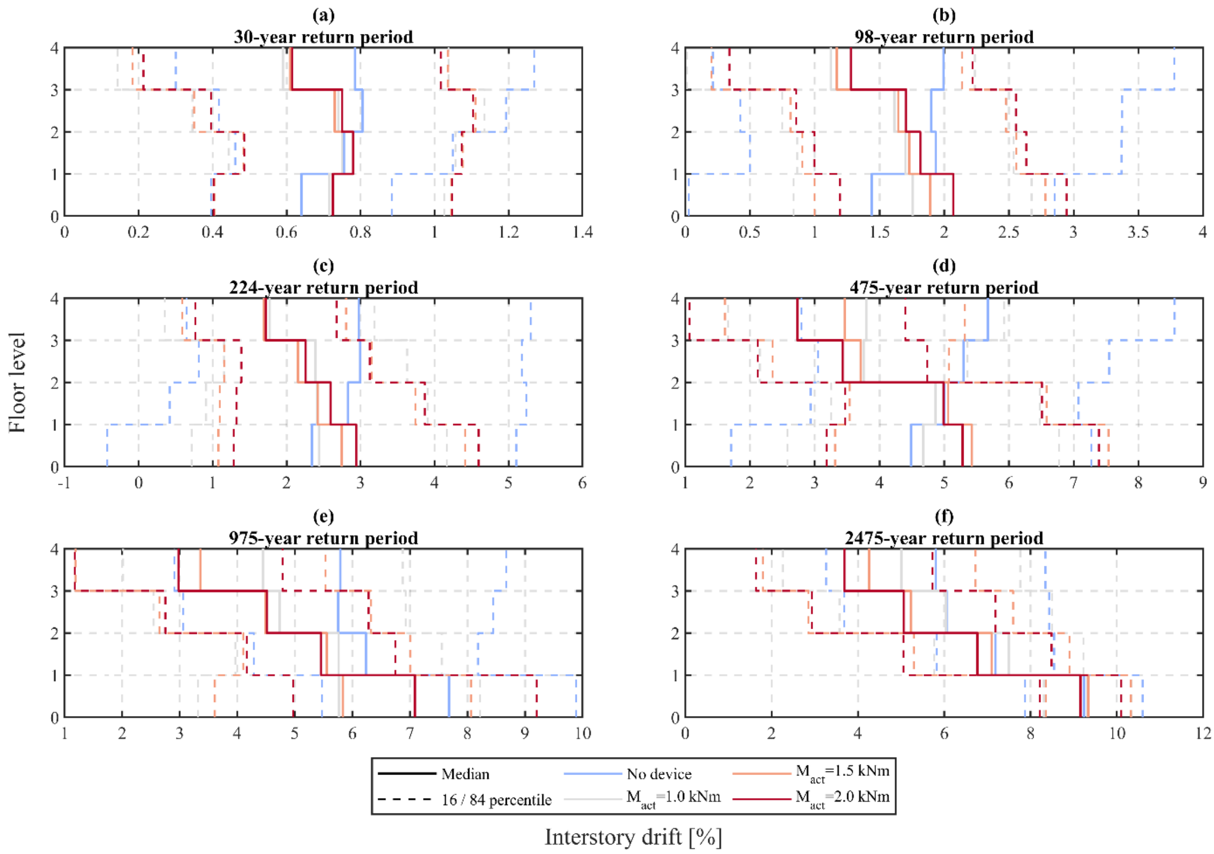

Figure 5 Interstory drift profiles for selected return periods.

As an example, the interstory drift profiles for the racking system under investigation are shown in Figure 5 for selected return periods.

As observed, for the racking system without the seismic protection device, the interstory drifts tend to increase with the height, unlike what is observed in the structures equipped with dissipative devices.

The opposite can be observed with the racks equipped with the device, where the peak of interstory is exhibited on the first floor. Considering the return period of 98 years, in both cases, the maximum value of interstory drift is approximately around 2%, if the median is taken into account. Another important change is given by the dispersion. It can be observed that when the device is installed, the dispersion of the results is significantly reduced.

As the return period increases, the beneficial effect of the friction-based seismic device in reducing interstory drifts becomes even more evident.

In particular, considering a return period of 975 years, the interstory drift at the first level reaches approximately 7.8% for the standard structure, while it drops to a minimum of 5.8% in the case of $M_{act} = 1.0$ kNm.

The same figure also illustrates how the stiffness of the base connections affects the seismic response by introducing significant interstory drift concentrations at the first level; this observation applies to all configurations with higher return periods but is particularly pronounced for the system without the dissipative device.

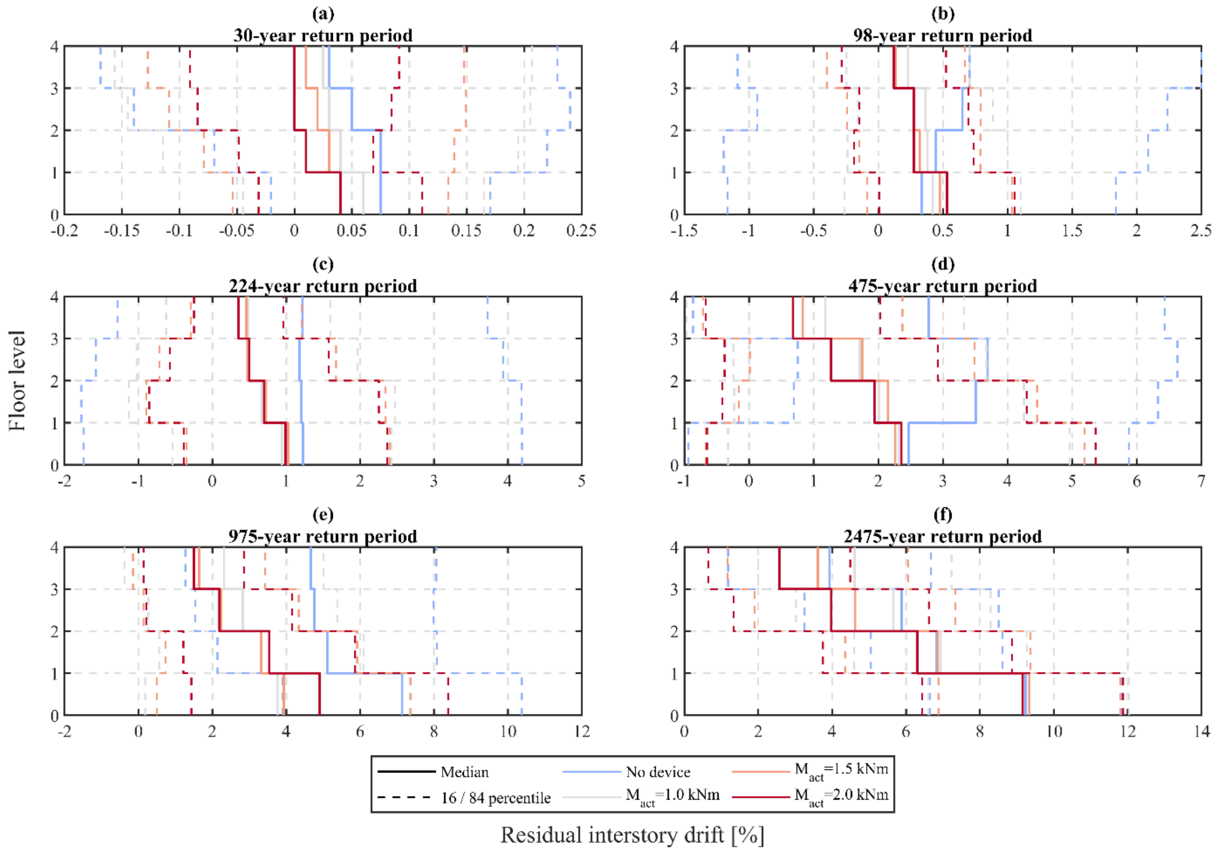

Figure 6 Residual interstory drift profiles for selected return periods.

Performing the nonlinear dynamic analyses, an additional analysis time of 5 seconds was added, leaving the rack in free oscillation; this permits the removal of the transient displacement and observation, therefore, only the residual displacements exhibited by the racks.

Hence, the computation of the residual interstorey drift was performed and depicted in Figure 6. In this figure, it is possible to note the influence of the devices in all circumstances since they significantly reduce the residual drifts, considering all the return periods. This is particularly important for the lower return periods, in which the complete operability of the systems after low-intensity earthquakes is expected.

3.3 Connection energy dissipation

The following section further emphasizes the effectiveness of incorporating the friction-based seismic device in the beam-to-upright connections of the racking system.

Its presence leads to an increase in the resistance of the connection itself in withstanding earthquakes, expressed in terms of greater energy dissipation, as well as a larger area under the hysteretic curve.

Through the diagrams presented in Figure 7, both the hysteretic curves, which represent the moment-rotation behaviour of the connection, and the energy dissipated by these connections after the seismic event, can be graphically observed.

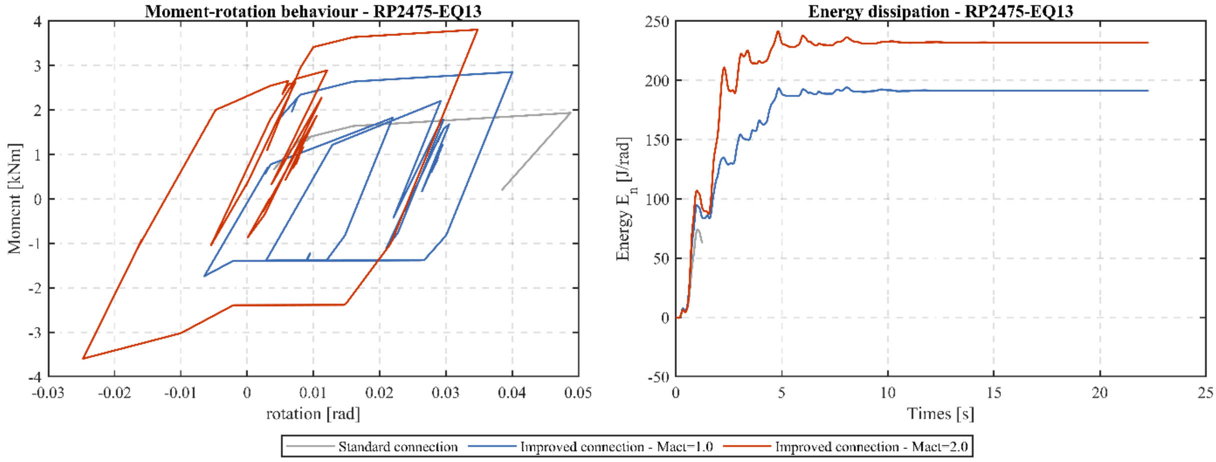

Figure 7 a) Moment-rotation behaviour for three different cases and b) corresponding energy dissipated during the earthquake.

Considering an earthquake with a return period of 2475 years, it can be observed that the rack without the dissipative solution, represented in grey, reaches collapse just a few seconds after the seismic event begins. This contrasts with the behaviour of the racking systems equipped with the friction-based seismic device in the beam-column connections, which show a different response. Both blue and red lines correspond to a device with a moment activation of 1 kNm and 2 kNm, respectively, and they were able to complete the analysis. The devices, as expected, improved the seismic performance of the rack, increasing the overall capacity of the connection and the energy dissipation. For this specific case, the presence of the devices avoids the collapse of the rack, highlighting, therefore, the importance and effectiveness of the mitigation strategy proposed here.

4 CONCLUSIONS

The seismic vulnerability of steel storage pallet racks was studied in this work. The focus was placed on the inherent fragility of these structures, with a future perspective of applying a seismic solution to mitigate this issue. The aim is to reduce the potential risk of collapse that can occur when these structures are affected by seismic actions, preventing significant economic losses and safeguarding the safety of workers.

In this regard, it is well-known that the seismic response of these structures is significantly influenced by the nonlinear behaviour of the connections. Therefore, seismic vulnerability was mitigated through the introduction of a seismic device within the beam-to-column connections. This steel device, by sliding, operates through friction and dissipates the energy produced by the seismic event. By accumulating the deformation required by the seismic event, it preserves the stability of the structure, which is inherently vulnerable due to the lack of plastic reserve that characterizes the members used in these systems.

In conclusion, the findings of this work show that the presence of the seismic device within the beam-to-column connections improves the seismic performance of the rack, reducing its vulnerability.

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