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PARAMETRIC STUDY ON THE MODELLING ASSUMPTIONS OF WOOD PALLET SLIDING

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Abstract

Although steel storage pallet racks seem like simple structures, their seismic evaluation is a difficult task. Their seismic response is characterized by flexible floor diaphragms and rather different response periods on their principal orthogonal directions (i.e., rigid in the cross-aisle direction and flexible in the down-aisle direction). There could be significant mass irregularities due to load and unload pallet processes, and typically, the mass sources (i.e., goods in wood pallets) are not attached to the steel frame. This characteristic can lead to the sliding of the pallets with diverse effects on the overall seismic response. On one hand, the sliding items can hit the steel frame with deleterious results or can lead to the fall of the pallets with damage to the stored items. On the other hand, sliding behavior reduces the total seismic mass as it detaches from the structure and also produces an additional energy dissipation through the friction between the pallet and the steel frame. This parametric study evaluates the sensitivity of the modeling assumptions of the sliding behavior of wood pallets, such as total weight, friction coefficient, seismic intensity, and sliding initial stiffness. The results show that the modeling assumption can significantly influence the sliding response, especially that of the sliding initial stiffness.

Keywords: Steel storage pallet racks, seismic demand, pallet sliding, nonstructural elements, parametric study.

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1 INTRODUCTION

The damage observed during recent seismic events has pointed out the importance of steel storage pallet racks in the seismic loss assessment of industrial facilities. Although steel storage pallet racks are widely used worldwide, the assessment of their dynamic behavior has not been studied thoroughly. There are different characteristics and parameters that influence the seismic response of steel storage pallet racks, such as cross-aisle and longitudinal periods, nonlinear response of the beam-upright and upright-ground connections, location and magnitude of loads and seismic masses, the sliding behavior of the pallets, etc. Such variability makes it difficult to accurately model the actual seismic behavior of steel storage pallet racks and, hence, the implementation of a performance-based design approach for such elements. A holistic approach to modeling steel storage pallet racks also requires the explicit modeling of the pallet's response to the seismic input.

To facilitate load and unload processes, the contents of steel racking systems, usually supported on wood pallets, are not fixed to the rack's beams. This configuration allows a sliding mechanism when static friction between the pallet and the steel beam is exceeded [1]. The sliding response of the pallets helps limit the maximum force experienced by the steel rack, as the inertial masses are not fixed to the structure, however, large sliding displacements can lead to pallets falling off from the racks, as shown in Figure 1, becoming an issue for life safety, economic loss, and operational performance objectives.

Figure 1 Damage to inventory on industrial storage racks in the 1994 Northridge Earthquake [2].

Different authors have studied the sliding mechanism of pallets on steel racks. For instance, Degee and Denoël [3] investigated the sliding response of pallets subjected to seismic forces, providing simplified models and verifying the favorable effect of the sliding mechanism on the rack's seismic response. Sideris et al. [4] characterized the dynamic response of palletized merchandise under earthquake excitation, generating shedding fragility functions and assessing the effects of inclined shelving on the seismic response. Jacobsen and Tremblay [5] conducted several shake table tests and their equivalent numerical simulations including pallet sliding. They highlighted the fact that although the model was able to reproduce the sliding response, the numerical results diverged from those obtained in the experimental campaign. Castiglioni et al. [6] tested, on a shake table, the sliding response of different pallet-rack configurations. Tsarpalis et al [7] used Newmark's sliding block analysis to simulate the sliding mechanism of pallets. Nuñez et al. [8] studied the influence of the pallet's sliding response on the seismic design of steel storage racks focused on the Chilean implementation. Tsarpalis and Vamvatsikos [1] proposed an empirical sliding prediction equation to evaluate the sliding response of steel racking systems based on actual ground motion information. These studies highlight the complexity and importance of properly modeling the sliding mechanism of pallets on steel storage pallet racks.

In order to quantify the reduction of the seismic demand on the rack due to the sliding mechanism, it is important to generate a holistic model in which the sliding response is explicitly modeled. To do so, several studies have simulated the pallet's sliding through flat slider bearings [5, 7]. This element allows modeling the interaction between a slider and a sliding surface, considering a friction model to calculate the force-velocity relationship. This study aims to numerically evaluate the influence of several parameters (i.e., friction coefficient, pallet weight, stiffness until sliding, and seismic intensity) on the pallet's sliding response when modeled as a flat slider bearing.

2 PARAMETRIC STUDY AND SEISMIC INPUT

A single pallet was simulated on OpenSeesPy version 3.7.0.4 [9], using a 2D simplified model composed of a zero-length element characterized by the properties of a flat slider bearing element, and another rigid element connecting the flat slider bearing to the center of mass of the pallet, assumed as one meter above the contact surface. Figure 2 illustrates the implemented 2D model. The pallet model was characterized by different parameters such as:

- Three friction coefficient (μ) values between the wood pallet and steel: 0.2, 0.3, and 0.4.
- Four pallet weights: 2.5, 5.0, 7.5, and 10.0 kN.
- Six values of stiffness until sliding of the flat slider bearing: 10^1, 10^3, 10^4, 10^5, 10^7, 10^9 kN/mm.

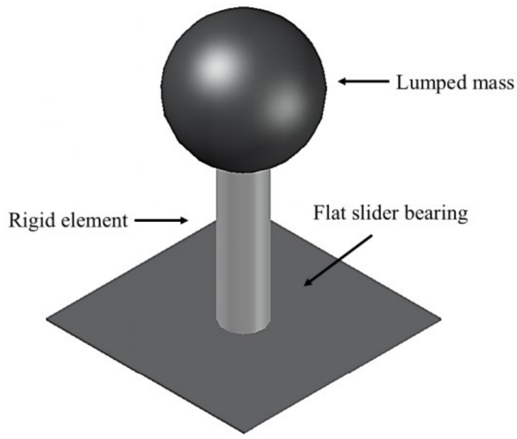

Figure 2 Sketch of the 2D pallet model.

The 2D pallet models were subjected to nonlinear time-history analyses using the FEMA P 695 [10] far-field ground motion set scaled to three increasing intensities based on the median spectral acceleration at 1.0 s. This set is composed of 44 horizontal ground motion records from historical strong seismic events around the world. Figure 3 shows the median acceleration spectra of the FEMA P695 far-field ground motion set scaled to the three considered intensities.

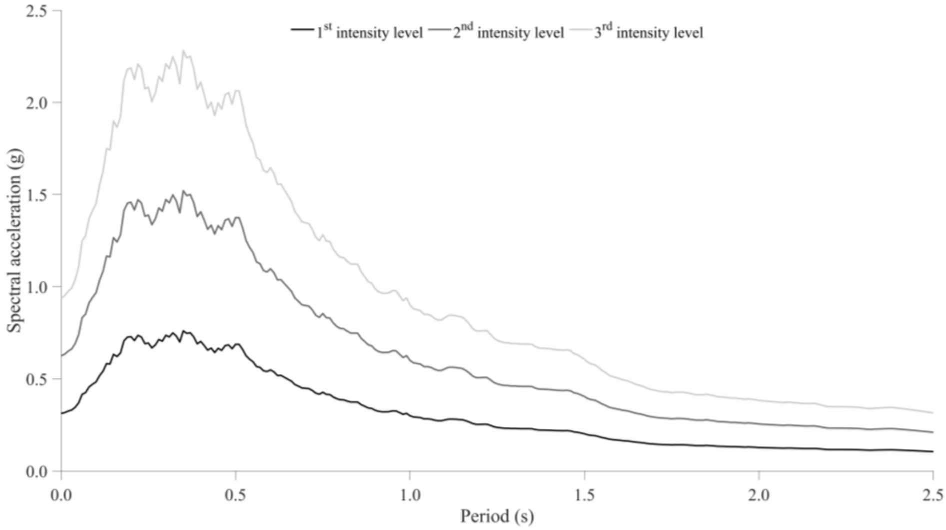

Figure 3 Median acceleration spectra of the FEMA P695 far-field ground motion set scaled to three intensity levels.

3 RESULTS

The simplified 2D pallet model was subjected to nonlinear time-history analyses using the aforementioned ground motion set, varying the friction coefficient, pallet weight, and stiffness until sliding. The pallet's sliding response was evaluated in terms of median peak displacement, median peak overturning moment, and median peak velocity. Figures 4 to 6 show the median response of the analyzed models; it should be noted that the different colors represent the studied pallet weights.

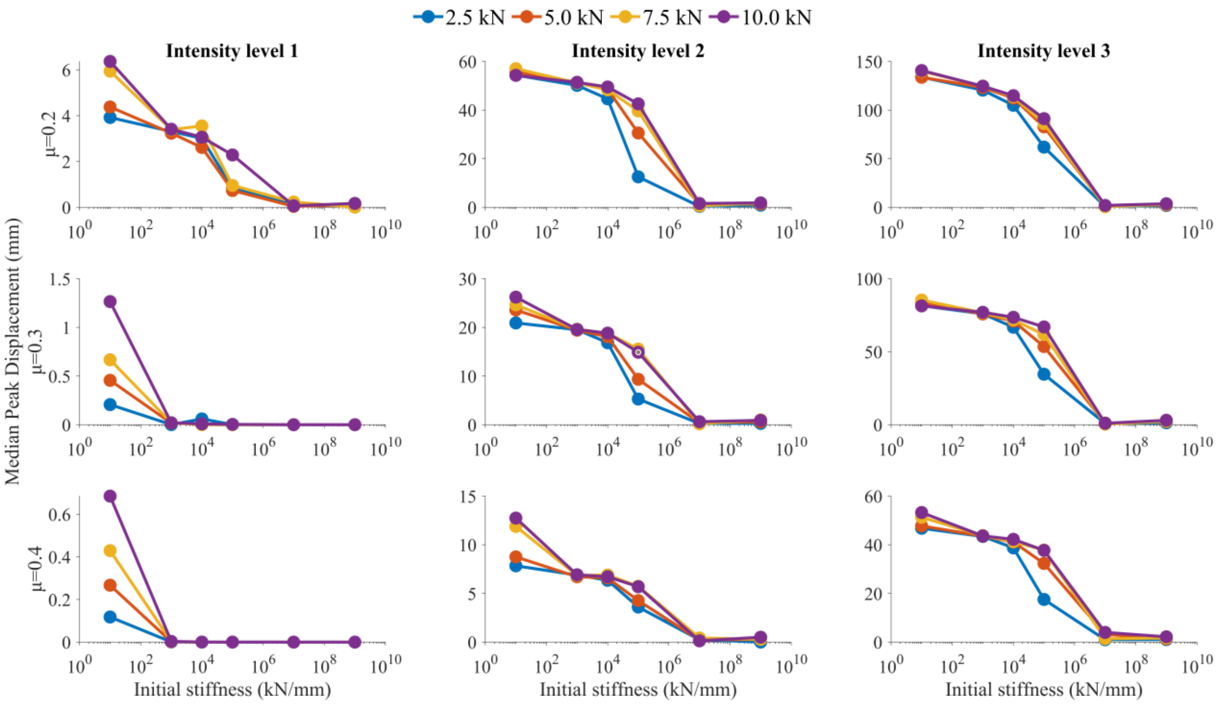

Figure 4 Median peak displacements of the analyzed pallet configurations.

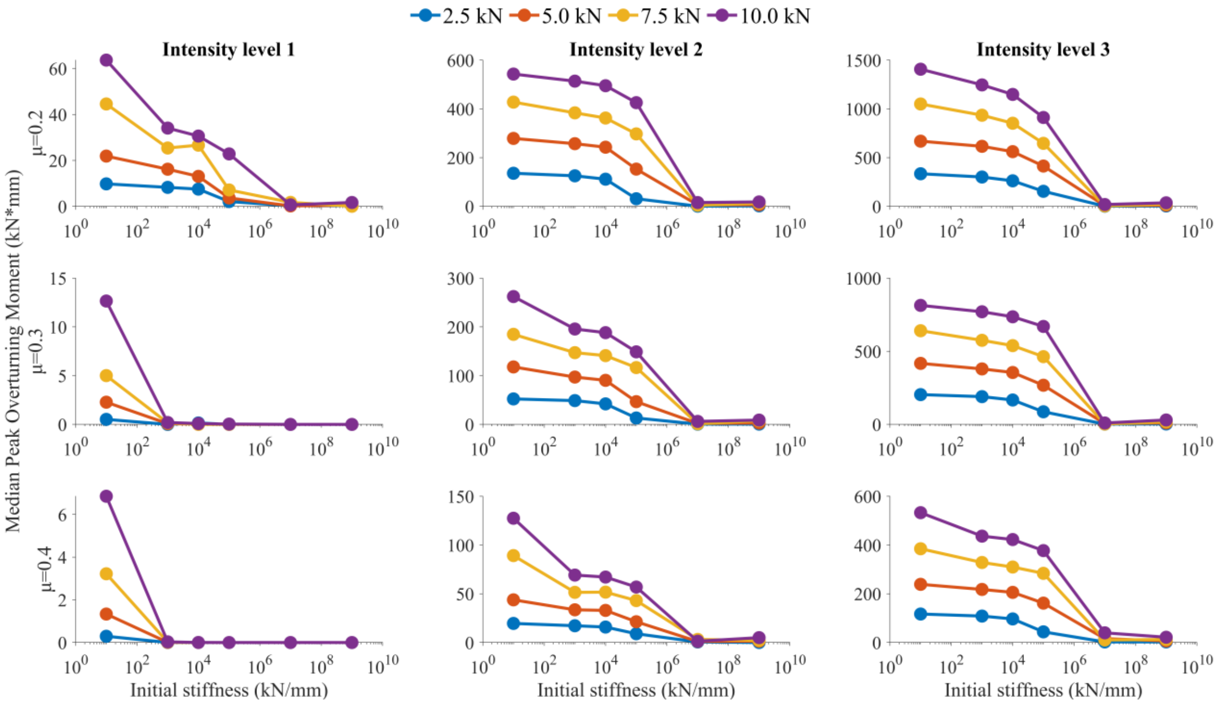

Figure 5 Median peak overturning moments of the analyzed pallet configurations.

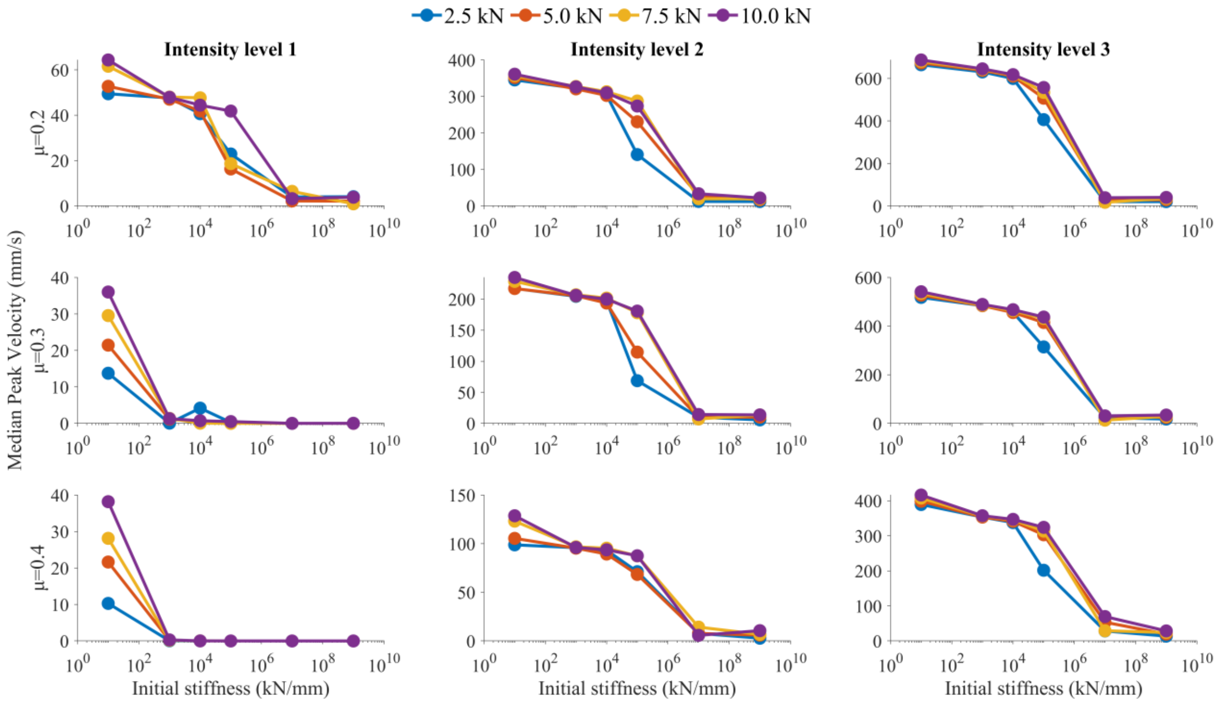

Figure 6 Median peak velocities of the analyzed pallet configurations.

The results show that displacement response is mainly influenced by the friction coefficient and the initial stiffness value. The former determined, as expected, the amplitude of the displacement, exhibiting larger median peak displacements as the friction coefficient reduces. For the latter, on the other hand, there is a slight reduction in the median peak displacements as the initial stiffness value increases up to 10^5 kN/mm, for larger initial stiffness values, the induced forces were not enough to reach the activation of the slider. In the case of the smaller intensity level, the same behavior was observed for friction coefficient equal and larger than 0.3 and initial stiffness values larger than 10^1 kN/mm. A similar trend was exhibited by the median peak velocity values of the pallet. Finally, for the median peak overturning moment, it is observed, as expected, an increment as the pallet weight increases due to the larger induced force. On the contrary, there is a reduction of the median peak overturning moment as the friction coefficient increases. Moreover, similarly as observed for the median peak displacement and velocity, the median peak overturning moment slightly reduces as the initial stiffness value increases up to an initial stiffness value equal to 10^5 kN/mm. For larger initial stiffness values, the pallet was not able to reach a sliding behavior. In addition, it was verified that the median peak horizontal force was equal to the expected friction force computed as the friction coefficient times the pallet weight. For the smaller intensity (i.e., intensity level 1), the pallets characterized by large friction coefficients (i.e., 0.3 and 0.4) and initial stiffness until sliding values larger than 10^1 kN/mm exhibited smaller median peak horizontal forces than that equal to the sliding force.

4 CONCLUSIONS

Recent seismic events have highlighted the importance of a proper evaluation of the seismic performance of steel storage pallet racks due to their crucial role in the logistic chain. Given the peculiarity of this kind of structure, such as flexible diaphragms, large variability of seismic masses in time, significantly different structural responses in the orthogonal directions, etc., it is important to produce holistic numerical models able to capture as accurately as possible the aforementioned properties. As the main seismic masses are not fixed to the structure (i.e., palletized merchandise), they can slide, reducing the induced seismic force on the system. However, larger sliding displacement can lead also to pallet shedding, which represents a failure mechanism or damage state of steel storage pallet racks that is not explicitly modeled. Different studies have investigated the impact of the sliding mechanism and proposed methods to numerically account for such behavior. Among them, the use of flat slider bearings to carry the pallet weight appears as a promising solution since it allows modeling explicitly the friction response between the pallet and the steel beans. In this regard, it is important to calibrate the different parameters that characterize the flat slider element to represent the sliding behavior of wood pallets. To fulfill this objective, a parametric study was conducted on a simplified 2D model of a single pallet. The sliding response was assessed in terms of peak median displacement, peak median overturning moment, and peak median velocity, varying the friction coefficient, pallet weight, initial stiffness until sliding, and seismic intensity. The conclusions of this study are summarized as follows:

- As expected, larger values of the friction coefficient reduced the median peak response values. In addition, larger seismic intensities induced larger median peak response values.
- The pallet weight did not influence significantly the median peak displacement and median peak velocity. On the other hand, it had a significant influence on the median peak overturning moment, exhibiting increasing overturning moment values as the pallet weight increased.
- The initial stiffness until sliding value played a fundamental role in the sliding response of the pallets. In general, the median peak response values showed a slight reduction as the initial stiffness values increased (i.e., ranging from 10^1 to 10^5 kN/mm). When the initial stiffness value was equal or larger to 10^6 kN/mm, the simplified models exhibited an almost zero response, which indicates that the flat slider was not able to reach a sliding behavior. It is important to highlight that for the smaller seismic intensity (i.e., intensity level

1) combined with large friction coefficient values (i.e., equal or larger than 0.3), almost zero median peak responses were observed for initial stiffness values larger than 10^1 kN/mm. Thus, this result represents a significant limitation in using such modeling techniques since no practical indications of extensive studies are available for selecting the proper initial stiffness values. As a consequence, further studies are currently in progress to assess reliable modeling strategies for simulating pallet sliding,

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