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Effects of pinching on seismic performances of unbraced steel storage pallet racks

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Abstract

Cold-formed steel storage unbraced pallet racks are generally used to store goods in large warehouses, and the existing full-scale shaking table tests show that a typical unbraced pallet rack exhibits a global failure mechanism with damaged connections and undamaged structural members. Therefore, the significant pinching of beam-to-upright connections has a significant influence on the structural seismic performance. The paper presents a numerical investigation into the effects of pinching on seismic performances of unbraced steel storage pallet racks. A FE model of cold-formed steel storage pallet racks subjected to seismic loads is developed to perform non-linear time-history analyses via OpenSees. The full-scale shaking table test results are employed to validate the FE model. Various connection models, including the modified Pinching 4 connection model, the hysteretic model, and the elastic model, are implemented in the simulation. The structural seismic performances based on different connection models are then compared. In particular, the connection behaviours defined by the modified pinching and hysteretic models are presented and compared. Moreover, the corresponding damage index (DI) of a typical connection is also calculated based on two different damage models. The results show that the pinching of connections greatly increases the structural seismic response in respect to the global displacement and inter-storey drift, and should be carefully considered in the seismic design of cold-formed steel storage unbraced pallet racks.

1. Introduction

Cold-formed steel storage unbraced pallet racks are generally used for storing goods in warehouses, and for the easy adjustment of storey height, the semi-rigid partial-strength mechanical beam-to-upright connections are employed. In this case, the stability of unbraced racks in the down-aisle direction depends greatly on connections behaviour, especially the beam-to-upright connections. The authors have conducted a series of static and cyclic experimental tests on steel storage rack beam-to-upright connections, i.e., boltless and bolted connections [1-3]. The results demonstrated that the storage rack beam-to-upright connections, classified as “semi-rigid” and “partial-strength” joints, exhibited moderate energy dissipation capacity and severely pinched hysteretic loops.

Several studies on seismic performances of rack structures [4] illustrate that the behaviour of unbraced pallet rack is similar to that of the moment-resisting frame, in which the seismic resistance of the overall structure is significantly influenced by the hysteretic behaviour beam-to-upright connections. However, in the current seismic design of rack structures, the hysteretic performance of connections is not accurately characterized leading to a overestimation of rack structural seismic resistance. Recently, Bernuzzi and Simoncelli [5-6] proposed an advanced design procedure for pallet racks in seismic areas, in which two joint models, i.e., EPK joint model and ACP joint model, are included. The ACP hysteretic joint model [5] takes the stiffness degradation into consideration, whereas it fails to capture the significant pinching and sliding characterization of connections. Based on substantial experimental results of cyclic behaviour of connections, the authors [2-3] employed the pinching4 model, as implemented in OpenSees software, to characterize the hysteretic behaviour of beam-to-upright connections.

This paper presents a numerical investigation of into the effects of pinching on seismic performances of unbraced steel storage pallet racks. A finite element (FE) model of cold-formed steel storage pallet rack subjected to seismic loads is developed to perform nonlinear time-history analyses via OpenSees. The full-scale shaking table test results are used to validate the FE model. Various connection models, including the modified Pinching 4 connection model, the hysteretic model, and the elastic model, are implemented in the simulation. The structural seismic performances based on different connection models are then compared. In particular, the connection behaviours defined by the modified pinching and hysteretic models are presented and compared. Moreover, the corresponding damage index (DI) of a typical connection is also calculated based on two different damage models. The results show that the pinching of connections greatly increases the structural seismic response in respect to the global displacement and inter-storey drift, and should be carefully considered in the seismic design of cold-formed steel storage unbraced pallet racks.

2. Finite element (FE) modelling and validation

As shown in Fig.1, a typical two-dimensional (2D) 3-storey 2-bay unbraced pallet rack is established in Opensees. The elastic beam-column elements are used to define the uprights and beams. Rigid column bases are specified in the FE model. Zero-Length elements serving as rotational springs are employed to represent the nonlinear behaviour of the connections, the material property of which is defined according to the experimental moment-rotation relationships. Herein, three connection models, namely elastic model, hysteretic model and author proposed Pinching4 model [2-3], are employed to study the effects of connection behaviour on structural seismic responses. A typical beam-to-upright connection, “2.3C1-B120-4T”, is considered in this study, and the hysteretic behaviours characterized by hysteretic and Pinching4 model are shown in Fig.2 (a) and (b), respectively. Note that the Rayleigh damping is used in the present FE models.

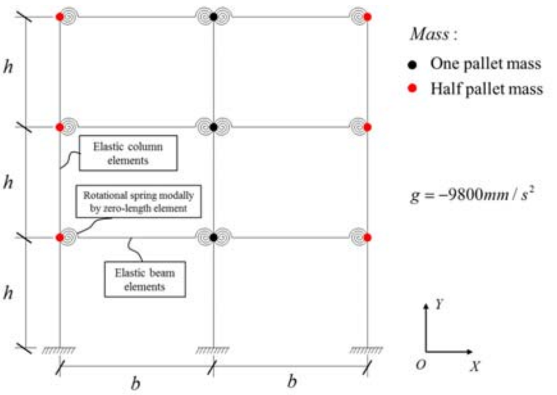
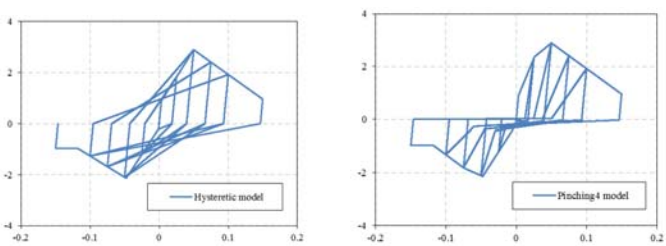


Figure 1: A typical two-dimensional unbraced pallet rack



(a) (b)

Figure 2: Hysteretic behaviour of a typical connection “2.3C1-B120-4T” characterised by: (a) Hysteretic model; (b) Proposed pinching4 model.

The FE model is validated against the full-scale shaking table test conducted by Chen et al. (1980) [7]. The comparison results of top storey displacement time-history curve between shaking table test and FEA model is illustrated in Fig.3, and a good agreement is achieved. Therefore, the proposed FE model can provide a reasonable accuracy in predicting the seismic behaviour of rack structures.

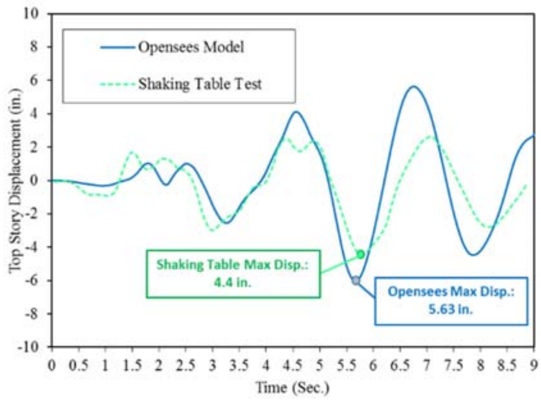


Figure 3: Comparison of top storey displacement time-history curve between shaking table test and FEA model

3. Evaluation of effect of pinching on structural seismic response

This section investigates the effect of connection pinching on structural seismic performances based on the proposed FE models. As listed in Table 1, five numerical models are established, and the nonlinear time-history analyses are then carried out. In this study, two commonly used connection models, namely, elastic model and hysteretic model and the author defined Pinching4 connection model are considered. Two different time-history acceleration records are considered, namely “El Centro N-S record from the 1940 Imperial Valley earthquake” and “Canoga Park record from the 1994 Northridge earthquake”, and the peak ground acceleration is taken as 0.7g. It should be noted that the models are labelled based on their specific model details. For example, “EP-PGA-0.7G” refers to a two-bay three-storey pallet rack with connections defined by the Pinching4 model (P) being subjected to El Centro ground motion (E) with a PGA of 0.7g.

Note that the FE model is analysed in three steps. First step is the eigenvalue analysis to obtain the first three modes and natural frequencies. Secondly, the gravity and live loads, assumed as the uniformly distributed loads along the pallet beams, are applied to the overall structure. Thirdly, the nonlinear time-history analysis considering geometric and material nonlinearities is performed.

Table 2: Model descriptions

Model ID	Connection Model	Applied ground motion	Peak Ground Acceleration (PGA) (Unit: G)
EP-PGA-0.7G	Pinching4 model	El Centro	0.7
EH-PGA-0.7G	Hysteretic model	El Centro	0.7
EE-PGA-0.7G	Elastic model	El Centro	0.7
CP-PGA-0.7G	Pinching4 model	Canoga Park	0.7
CH-PGA-0.7G	Hysteretic model	Canoga Park	0.7

Figure 4 presents the comparison of time-history top-storey displacements calculated by the Pinching4, Hysteretic and Elastic models. It can be observed from the figure that in the elastic range before degradation occurred (t<3s), the curves of these three models are consistent. When the connections entered into the inelastic range, the degradation occurred. The storey displacement calculated by the pinching model is significantly greater than that obtained from the hysteretic model. In addition, the frequencies of the structure were also observed to be degraded with the deterioration in stiffness and strength of connections. Therefore, it can be concluded that the connection models with varied degradation rules can significantly influence the seismic responses of the overall rack structures. The same results can be derived from the structures subjected to the Canoga Park ground motion, as highlighted in Fig.5.

The highest value of the top storey displacement when the structure was subjected to the same seismic excitation is obtained for the FE model with Pinching4 connection model. The comparison results indicate that the severely pinched hysteretic connection response characterized by Pinching4 model greatly influences seismic performance of the overall rack structure, and without considering the effect of pinching, the overestimation of structural seismic response is obtained.

Furthermore, the connection damage is evaluated for the safe use of structures after earthquake. Moment-rotation relationship and time-history rotation responses of critical beam-to-upright connections are derived from the FEA models. The Damage Index (DI) of critical connections defined by various connection models are calculated by Miner damage Index [8] and Cumulative ductility index [9]. Figure 6 presents the damage accumulation of the critical connection represented by the Miner damage index and the cumulative ductility index, in which the x-axis represents the number of loading cycles and the y-axis is the value of accumulative damage index. It can be seen from the figure that the results derived from different damage models are quite different, but for the pallet rack subjected to the same ground motion, the damage index (DI) derived from the model with pinching connections is significantly greater than that with hysteretic connections.

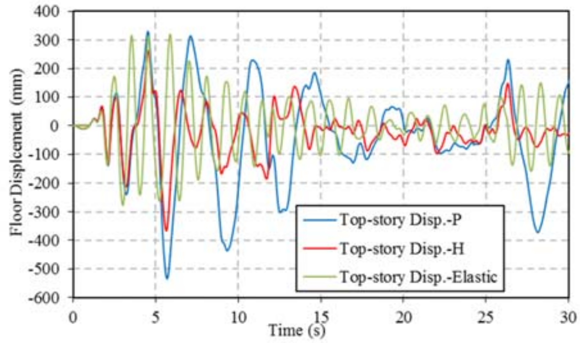


Figure 4: Time history top-storey displacement calculated by the models varied in connection models, i.e. “EP-PGA-0.7G”, “EH-PGA-0.7G” and “EE-PGA-0.7G” (under El Centro ground motion)

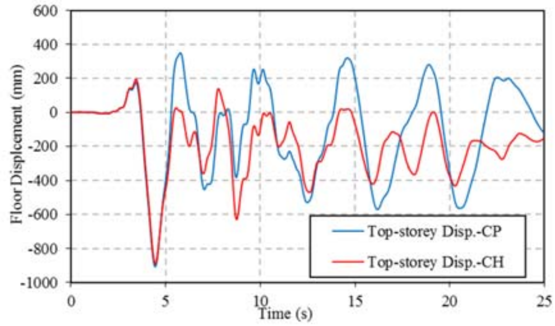


Figure 5: Time history top-storey displacement calculated by the models varied in connection models, i.e. “CP-PGA-0.7G” and “CH-PGA-0.7G” (under Canoga Park ground motion)

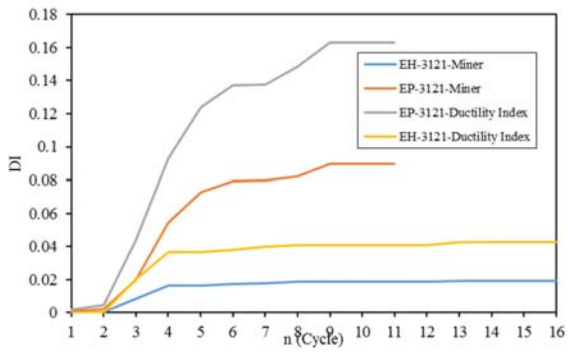


Figure 6: Relationship of damage index (DI) versus the loading cycles for a critical connection based on the Miner’s rule and Cumulative ductility method

4. Conclusions

This paper presents a numerical investigation into the seismic performances of cold-formed steel storage unbraced pallet racks with an emphases on the effect of pinching on the rack structural seismic responses. A two-dimensional FE model for unbraced rack structures is developed with the implementation of various connection models. Comparisons between FE models and full-scale shaking table test results are made, showing that the developed FE model is capable of predicting the seismic behaviour of cold-formed steel storage pallet racks. The validated FE model is then used in nonlinear time history analyse for the purpose of evaluating the influence of connection models on the structural seismic performance. The connection behaviours defined by the pinching and hysteretic models are presented and compared. It can be observed that the predicted results of pinching and hysteretic models are identical when connections are in the elastic range. As the connections start to degrade, the structural response of the pinching model is generally more severe than that of the hysteretic model. The corresponding damage index (DI) of a typical connection is also calculated based on two different damage models. In general, the effects of connection pinching on the rack structural seismic responses cannot be ignored, and should be carefully evaluated in structural analysis.

5. Acknowledgments

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