Advanced Seismic Design for Storage Pallet Rack Steel Frames

Claudio Bernuzzi[1] and Marco Simoncelli[1, a)]

[1]*Department of Architecture, Built environment and Construction engineering (ABC), Politecnico di Milano, Italy.*

[a)]Corresponding author: marco.simoncelli@polimi.it

Abstract. In the paper, a study on the design of braced and unbraced steel storage pallet racks in seismic zone is summarized. On the basis of a geometric layout of interest for routine design, rack performance has been evaluated via two alternative approaches: the well-established modal response spectrum analysis (MRSA) and an advanced strategy combining non-linear time-history analyses with the measurement of the damage in joints. Reference is made to two recent Italian earthquakes scaled by different values of the peak ground acceleration. Furthermore, cyclic joint behavior has been reproduced by means of a suitable model accounting for joint strength/stiffness degradation, whose excursions in plastic range has been considered to monitor the damage.

SHORT INTRODUCTION

An important area of the steel construction industry is nowadays represented by structural systems made by thin-walled cold-formed components [1], which are extensively employed for logistic applications to realize frames used for the long- and medium-term storage of goods and products. One of the most common types of storage solutions is the so-called adjustable selective storage pallet rack (in the following simply identified as “rack”), which is the core of the present short paper. The vertical elements (uprights) are jointed with diagonals and struts in the transversal (cross-aisle) direction forming a set of trussed columns connected in the longitudinal (down-aisle) direction to each other by pairs of pallet beams directly supporting the stored goods. At each beam end, generally, a shop welded bracket with hooks is accommodated into special slots regularly pitched along uprights allowing for a rapid assemblage of the skeleton frame [2]. In the past, due to both economic needs and logistic reasons, bracing systems (spine bracings) were rarely used in the down-aisle direction. More recently, especially in seismic countries, several braced racks have been realized to resist more efficiently against earthquakes owing to the importance of preventing overall collapse.

For the seismic design in accordance with the European practice, reference must be made to the EN16681 [3] provision, dealing with the design strategies and the key features of racks. The most accurate approach for the seismic analysis is the nonlinear time history (NLTH) method that can be always adopted, by selecting at least seven different spectrum-compatible accelerograms and considering design parameters as mean values. Otherwise, other prescribed methods are the lateral force method (LFM) and the modal response spectrum analysis (MRSA), both based on the design response spectrum obtained by scaling the elastic response spectrum by means of the well-known behavior (q) factor [4]. Furthermore, in both LFMA and MRSA methods, the degradation of the rotational stiffness and of the flexural resistance of the connections is totally neglected, which is due to the loading and unloading sequences in the plastic range. An unstable behavior of the cyclic response of beam-to-column and base-plate joints [5] has been experimentally observed. Unlike joints for the more conventional steel buildings, the hysteretic behavior of rack joints is always characterized by a remarkably progressive and regular degradation of both stiffness and strength, with a non-negligible pinching. Despite these non-negligible limitations, the MRSA method is very frequently adopted in the routine design by engineers.

In this short paper, a study is summarized, dealing the differences associated with the application of NLTH and MRSA approaches on racks of interest for practical design. Reference has been made to braced and unbraced racks located in different seismic zones. Moreover, the NLTH approach has been improved by considering also the joints fatigue by using the low-cycle fatigue theory (LCF) already proposed in literature [6].

THE PROPOSED ANALYSES

Seismic Standards [3,4] give prescriptions only about the evaluation of the ground motion as well as of the definition of suitable criteria to simulate the effects of the loads (pallets) under earthquake, for racks as well as for other types of structures. Safety checks are carried out always using the rules proposed for monotonic design, which strictly depend by the method of analysis and in the following, reference is made to the General Method (GEM) [6].

The layout of the considered racks is reported in Fig. 1, together with the cross-section of uprights, pallet beams and bracing systems (diagonal members along the cross-aisle direction in the upright frames). The number of bays is equal to 7 with a length of 2.7m. The width of the upright frame, with the typical V-panel, is 1.1m. The height of the interstory of the storage levels is constant and equal to 2.0m (the total height of the racks is 8.0m). For the braced configuration, it has been chosen to locate the bracing towers in correspondence of the external bays in order to avoid torsional effects. All the bracing elements (diagonals, horizontal and vertical bracings) have been modelled via *truss* elements, while *beam* elements reproduce the response of uprights and pallet beams. Furthermore, despite the non-negligible influence of the asymmetry of the masses on the structural behavior, the sole condition of fully loaded rack has been herein considered and pallet units have been simulated via a uniform distributed load on each pallet beam. The base of uprights has been considered perfectly fixed to the industrial pavement in order to limit the number of variables of the present study. Members response has been assumed always in elastic range, while beam-to-column joints have been modeled by using a multi-linear rotational spring with hysteretic behavior.

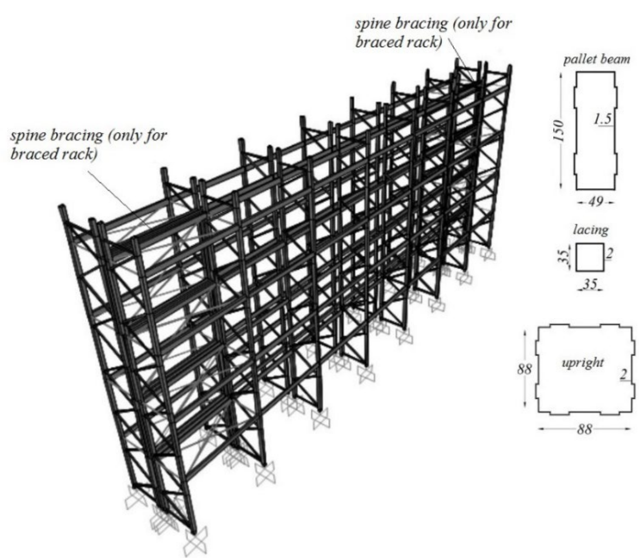

FIGURE 1. The considered steel storage rack frame and its main components.

Preliminarily to the seismic analyses, the evaluation of the static rack performance has been appraised via the iterative application of the GEM. For each of the considered racks in Table 1, the values of the safety index of the most highly stressed upright (U), pallet beam (B) and beam-to-column joints (J) are reported together with the live load (LL) over dead (DL) load ratio. The LL/DL value is of great interest for commercial reasons because it expresses directly the structural efficiency, being the rack costs proportional to the amount (weight) of steel of the skeleton frame. Furthermore, in the same table also the value of the elastic critical buckling load multiplier (α_{cr}) is reported.

TABLE 1. Key data related to the static performance.

unbraced					braced				
SI_U	SI_B	SI_J	LL/DL	α_{cr}	SI_U	SI_B	SI_J	LL/DL	α_{cr}
0.97	0.98	1.00	83.2	2.55	0.87	1.00	0.94	103.7	8.85

It can be noted that both solutions represent an economic optimization of the frame being all the safety indexes (SI) very similar one another and close to unity or slightly lower, with the high ratio LL/DL for unbraced (83.2) and braced (103.7) racks, respectively, confirming the great convenience of these structural systems.

As to the seismic input, two different locations in Italy have been considered: Mantua, MN, (Soil type D, topography T2) and L'Aquila, AQ, (soil type E and topography T4), where strong earthquake occurred in 2012 and 2009, respectively. The associated elastic spectra have been defined according to the Italian code for structural building design (NTC2018) and for each of them four different spectra have been obtained by scaling the original one via an α_g multiplier assuming the values of 0.1 (reduction to 90% from the observed one), 0.3, 0.5 and 1 (no reduction, i.e. the peak ground acceleration is the observed one). Seismic action was always considered along the down-aisle direction, that is the weakest one with reference to the seismic response. The MRSA approach can be associated with an iterative procedure, such as the one summarized in Fig. 2, to identify the load carrying capacity (W_{seis}^{MRSA}) associated with the seismic event of interest, once defined the q-factor value. In particular, starting from a tentative value of the vertical distributed load on the beam (W_{tent}), which simulates the effect of the stored units, MRSA analyses are performed until the value of the tolerance (tol) is reached. In particular, W_{tent} has to be updated and new iterations are required.

Regarding the analyses, the MRSA approach has been applied by considering q values ranging from 1 to 5. It can be noted that, generally the most common used values are 1.0, 1.5 and 2 which are consistent with the European standard requirements [3]. Furthermore, the high values (i.e. 2.5, 3, 4 and 5) are inside the range defined by research outcomes associated with recent pushover experimental studies.

As to the NLTH-LCF approach [7], for each of the 8 seismic inputs (2x4), 10 synthetic ground motion spectrum-compatible earthquakes (total duration, t_{max} = 20s) have been generated by using the well-known SIMQKE software (downloaded at http://gelfi.unibs.it/software/simqke/simqke_gr.htm, 2020), after the selection of the i-th accelerogram with a duration of t_{max}, the starting point is the definition of a tentative seismic design load. For each of the integration steps, having an equal duration of Δt, the set of generalized forces and displacements is recorded to be used at the end of the analysis to assess the safety index for members (SI^k) and the accumulated damage for joints (D^k). If the difference between SI^k (or D^k) and the unity exceed the pre-fixed tolerance (tol), the analysis has to be repeated reducing or increasing the value of the distributed load on pallet beams.

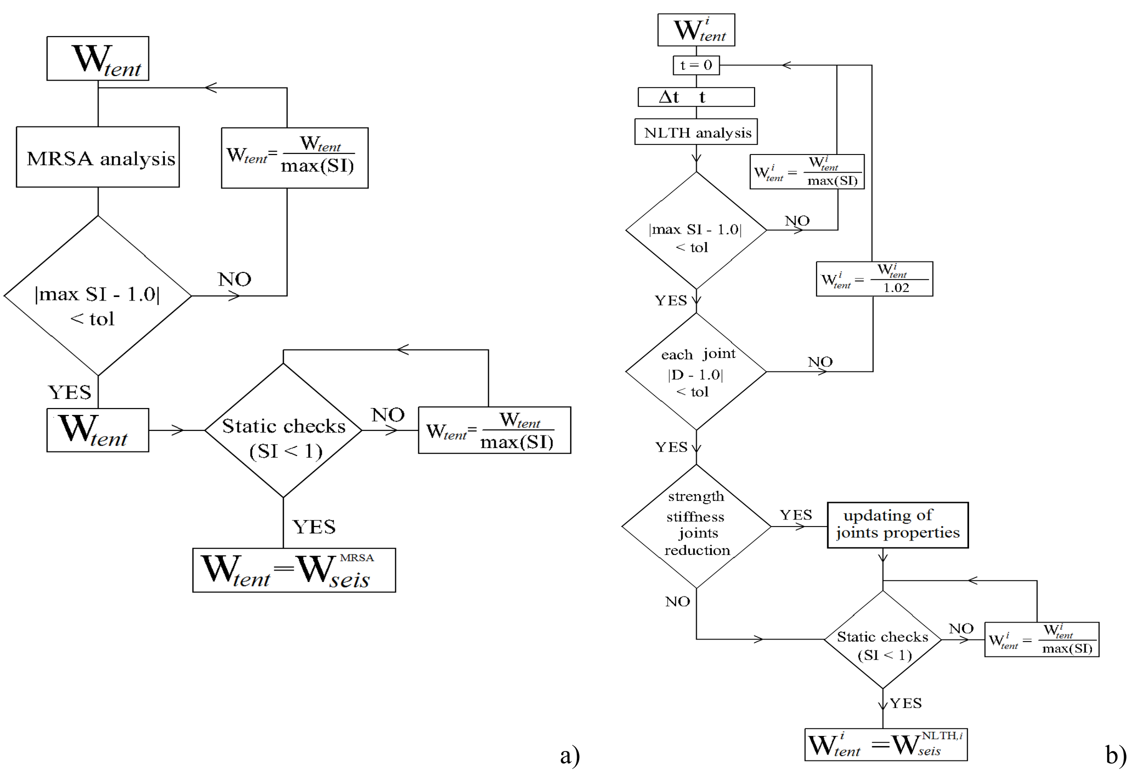

FIGURE 2. Flow-chart of the considered design procedures: a) MRSA and b) NLTH-LCF

DISCUSSION ON THE RESULTS

As to the considered braced and unbraced racks, 112 MRSA and 160 NLTH analyses have been performed to assess iteratively the load carrying capacity in different seismic zones. Main outcomes of this research are:

- as to the MRSA approach, a limited difference in q (q=2 instead of 1.5 or q=1.5 instead of 1) has a significant impact on performance of the unbraced racks. Otherwise, the influence of the behavior factor (q) value on the braced racks is more limited;
- as to the NLTH-LCF approach, it has been underlined the importance of the monitoring of the damage in joints due to cyclic excursions in the plastic range that cannot be neglected for a safe use of the rack during its total service life, especially when severe earthquakes occur in unbraced rack configuration;
- the direct comparison between the performances assessed via the two considered approaches stresses out, once again, the great importance of the q value. A great dispersion of the value of the behavior factor to be adopted in the MRSA approach to obtain the performance assessed via NLTH-LCF approach, that is q* reported in Table 2;
- the proposition of a unique q value, independently of the geometric layout and component performance, to be used for designing storage racks appears to lead, in many cases, to an unsafe and/or un-optimal design.

TABLE 2. Proposed equivalent q* factor

	α_g	Unbraced	Braced
AQ	0.1	1.88	1.15
	0.3	1.77	1.02
	0.5	2.37	1.00
	1.0	3.25	1.14
MN	0.1	2.85	1.00
	0.3	1.55	1.15
	0.5	1.71	1.02
	1.0	2.40	1.01

In general, it can be stated that when racks are used in seismic zones, the braced solutions are, of course, very convenient in term of performances. Furthermore, unbraced racks often can efficiently be used in low- and medium seismic zones, if a refined procedure of analysis, like the NLTH-LCF one, is adopted. Finally it is worth noting the great difference in terms of load carrying capacity, and hence of the racks cost, associated with these two different design strategies for seismic design. Future development in the seismic racks design researches should be focused on the field of structural robustness in accordance with a methodology already assessed [8] for traditional steel structures.

REFERENCES

1. N. Baldassino, C. Bernuzzi and M. Simoncelli, "Evaluation of European approaches applied to design of TWCF steel members", in *Thin-Walled Structures,* **143**, 106186 (2019).
2. N. Baldassino, C. Bernuzzi, A. Di Gioia and M. Simoncelli, "An experimental investigation on solid and perforated steel storage racks uprights", in *Journal of Constructional Steel Research*, **155**, 409-425 (2019).
3. EN16681 "Steel static storage systems – Adjustable pallet racking systems – Principles for seismic design", CEN European Standard, Brussels (2016).
4. EN1998-1, "Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings", Brussels (2004).
5. C. Bernuzzi and C.A. Castiglioni "Experimental analysis on the cyclic behaviour of beam-to-column joints in steel storage pallet racks", in *Thin-walled structures*, **39**, 841-859 (2001).
6. C Bernuzzi, B. Cordova and M. Simoncelli "Unbraced steel frame according to EC3 and AISC provisions", in *Journal of constructional steel research*, **114**, 4274, 157-177 (2015).
7. C. Bernuzzi and M. Simoncelli "Steel storage pallet racks in seismic zones: Advanced vs. standard design strategies" in *Thin-Walled Structures*, **116**, 291-306 (2017).
8. R. Zandonini, N. Baldassino and F. Freddi "Robustness of steel-concrete flooring systems – An experimental assessment", in *Stahlbau*, **83** (9), 608-6013 (2014).