# Seismic Performance Monitoring and Identification of Steel Storage Pallet Racks

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**Abstract.** Steel storage pallet racks are framed steel structures commonly used in the logistic field. According to the European practice, they are built with cold-formed steel profiles. Vertical and horizontal elements are connected with mechanical joints and special elements are used for the base connections. The design of these structures is usually performed by adopting the 'design by testing' approach. This procedure asks for the experimental characterization of the main racks components and sub-assemblies, which allows identifying the parameters needed for the safety checks and the development of reliable FE models. Recent seismic events clearly showed the need for improvements in the knowledge of the seismic response not only of the components but also of the whole structure. As a contribution to this topic, an experimental study of the seismic response of full-scale rack frames is currently in progress. At this aim, a testing set-up for full-scale structures, with a maximum height of 22m, was designed and realized. In this paper, the main features of the experimental set-up and the results of two push-over tests on a commercial two-bay four-level pallet rack are described and discussed. Finally, the results of FE analyses are presented.

**Keywords:** Seismic Performance Monitoring, Structural Identification, Steel Storage Racks, Cold-formed Profiles, Full-scale Tests, FE Model Updating.

## 1 Introduction

Steel storage pallet racks are typical framed steel structures used for storing goods and products and are made of cold-formed steel profiles (Fig. 1) [1].

The vertical elements, i.e. the uprights, are usually thin-walled open mono-symmetric sections provided with a regular pattern of perforations along their length to allow the connection with the beams and the bracing system elements. The beams are usually thin-walled boxed sections and, at their ends, are welded to brackets that realize the connections with the uprights. Bracing systems are usually located only in the transversal direction (cross-aisle direction), while the stability of the frame in the longitudinal direction (down-aisle direction) is provided by the semi-continuity of the base-plate and beam-to-column connections. The performance of these connections is characterized by a non-symmetric behaviour and a marked non-linearity. The slenderness of the elements composing the racks makes the structure quite sensitive to instability and second-order effects. Furthermore, racks are characterized by limited dead loads if compared to live loads.

**Fig. 1.** A typical steel storage rack (courtesy of Metalsistem S.p.A.).

In case of collapse due to seismic or accidental actions, the loss of money associated to the loss of stored goods is higher than the costs of restoration of the structure itself (Fig. 2).

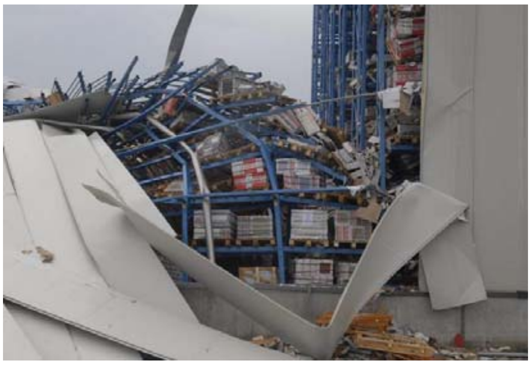


**Fig. 2.** Collapse of a storage rack happened in Emilia-Romagna earthquake event.

The design of these structures is quite complex due to all the mentioned features and, usually, a mixed experimental-analytical approach is adopted [2,3,4,5,6]. The elements and sub-assemblages are tested, following the well-known procedure of the ‘design by testing’, in order to evaluate the parameters to be adopted in the design phase or to be used in FE numerical models. Seismic actions add complexity to the design procedure and stress the need of an in-depth characterization of the components and of the whole structure [7].

Recently a study of the seismic response of steel storage pallet racks was activated by the University of Trento and the Politecnico di Milano, in cooperation with the rack manufacturer company Metalsistem S.p.A.. In this framework, full-scale tests on typical pallet racks were performed by using a testing set-up able to apply both gravitational and horizontal loads. In this paper, the main features of the experimental set-up and the results of tests performed on a two-bay four-level rack are presented and discussed. In addition, the preliminary results of FE numerical models are compared with the experimental outcomes.

## 2 The Experimental Set-up

The experimental set-up was designed and built up by the Research and Development Division of Metalsistem S.p.A.. It consists of a rigid steel trussed tower which acts as a reaction frame [8]. The tower has a total height of 24.5m and has plane dimensions of 12.35m x 12.35m and allows testing structures with a maximum height of 22m (Fig. 3).

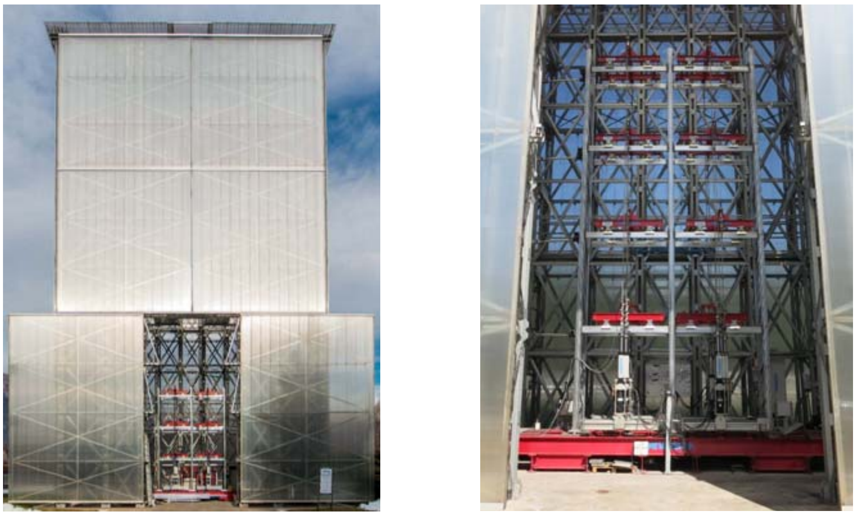
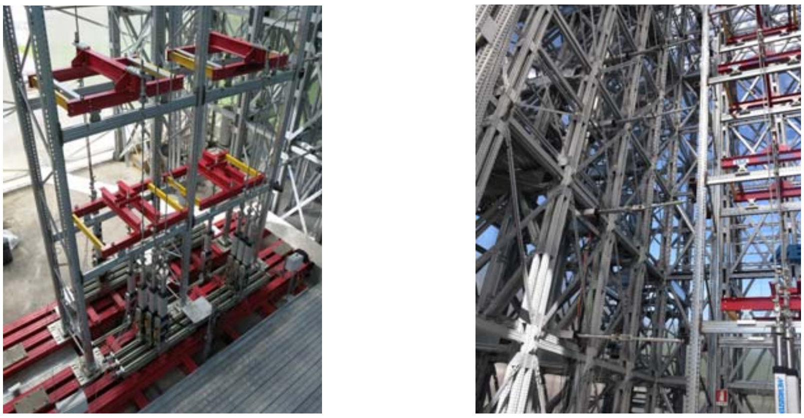

(a) (b)

**Fig. 3.** The testing tower: external view (a) and a rack under test (b).

The tower is equipped with six couples of dynamic actuators, which allow applying the vertical loads. In order to follow the structure sway during the loading phase, maintaining the verticality of the loads, the actuators move on rail beams (Fig. 4a). A counter-beams system is pinned connected to each pallet beam to transfer at its quarters the vertical loads transmitted by two independent actuators. Horizontal dynamic actuators (Fig. 4b), taking reaction on the steel tower, permit the application of the horizontal forces at different heights allowing for the execution of push-over dynamic tests.



(a) (b)

**Fig. 4.** The loading equipment: vertical (a) and horizontal (b) load system.

All the dynamic actuators are coupled with loading cells, which allow measuring the applied load. The horizontal displacements at each beam level are measured through wire transducers (red boxed in Fig. 5a). Both the loading cells and the wire transducers measurements are automatically recorded during all the testing phases.

(a) (b)

**Fig. 5.** The instruments set-up. Horizontal wire transducers: global view (a) and detail (b).

## 3 The Case Study

The experimental study was performed on two nominally equal frames with two bays and four stories. The length of each bay was 1.8m and the inter-storey was 2m, with a rack total height of 8.5m. The width of the frame in the cross-aisle direction was 1m with a V-type bracing system having a height variable from 0.7m to 1.4m.

The upright has a mono-symmetric open cross-section with a thickness of 2mm and is characterized by regular perforation systems along the whole length. The beams are closed bi-symmetric sections obtained from coils having a thickness of 1mm (Fig. 6). The upright is a class 4 profile while pallet-beams and lacings are in class 3 according to the classification criterion of Eurocode 3 part 1-1 [9].


(a) (b)

**Fig. 6.** Details of uprights (a) and beams (b).

A detail of the beam-to-column connections is reported in Fig. 7a. Owing to the need of reducing the number of parameters affecting the experimental results, ideal hinges have been located at each upright base (Fig. 7b), due to the non-negligible influence of the base-plate connections on the racks response. The hinged connections have been realized by means of cylindrical pins located in channel grooves of two thick steel plates.


(a) (b)

**Fig. 7.** Details of the beam-to-column joints (a) and the base-plate hinges (b).

Preliminarily to full-scale tests, component tests have been executed, to obtain the main data characterizing the profiles and the beam-to-column joints. In particular, the effective area and section modulus of the uprights and the moment-rotation relationship of beam-to-column joints have been determined according to the EN15512 standard [10].

## 4 The Experimental Programme and the Test Results

The loading scheme adopted in the tests is presented in Fig. 8.

The following testing procedure was adopted:

i) the vertical loads were first applied on the rack bays and maintained constant during all the testing phases. In the first test the total value of the vertical force was of 80kN, while in the second one the load was doubled, i.e. 160kN;

ii) the settling of the specimens was obtained imposing cycles generating small horizontal displacements;

iii) horizontal forces were increased up to the achievement of the rack collapse, by imposing a triangular inverse load pattern (according to the first modal shape of the frame).

After collapse, frames were unloaded and the residual deformations measured.

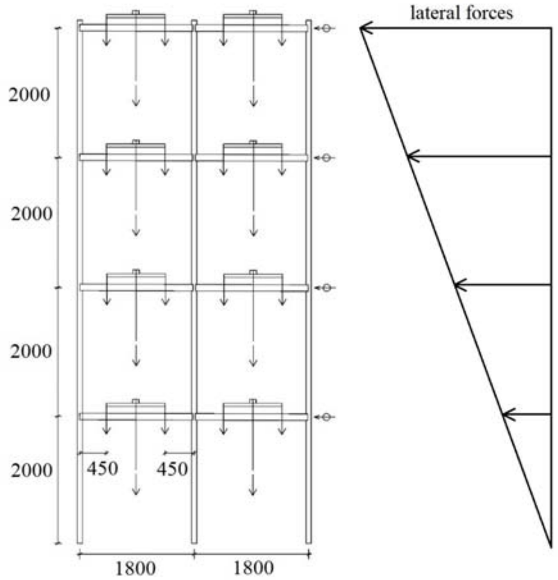


**Fig. 8.** Schematic view of the tested rack (measures in mm).

For both racks, the observed failure mode was characterized by sway buckling in correspondence of the first inter-storey, with plastic deformations of the nodal zones close to the first load level (Fig. 9).

(a) (b)

**Fig. 9.** Deformed shape of one frame at collapse (a) and detail of the connections (b).

The “capacity curves” of both frames are compared in Fig. 10 in order to assess directly the influence of the gravity load. By doubling the vertical loads, a decrease of the maximum base shear force of approximately 35% can be noted, while no remarkable influence on the maximum plastic displacement is observable.

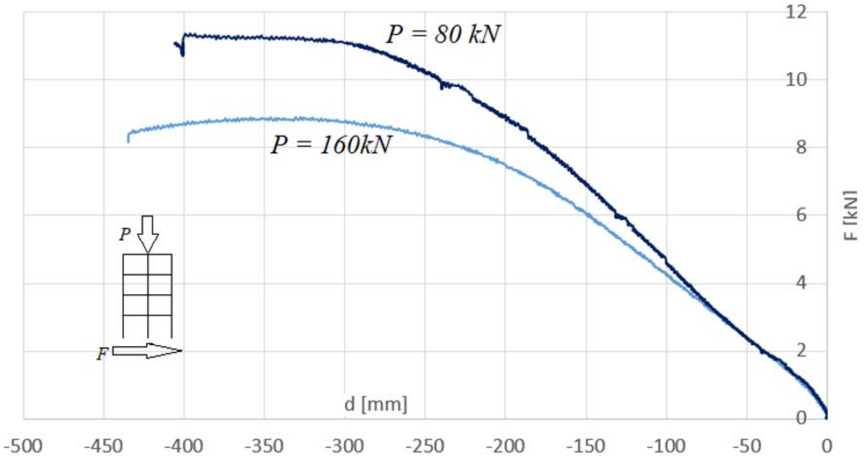


**Fig. 10.** Capacity curves of the studied frames: total base shear F versus top displacement d.

It should be mentioned that the current rack Standards do not provide '*ad hoc'* rules for full-scale tests, as the ones here presented. In addition, the actual version of the Italian building code accepts an experimental evaluation of the behaviour factor (q) of racks via pushover tests. No practical indications on the level of gravity loads are provided, although this parameter remarkably influences the pushover curve, as shown in Fig. 10.

## 5 Numerical Simulations

FE numerical models were developed via an academic finite element software called Śiva, having beam elements with the 7th degree of freedom [11]. Pallet-beams and lacings have been modelled as elastic members. In the uprights, perforations have been accounted for by using the equivalent cross-section approach, in accordance with the prEN15512:2018 [12]. Non-linear springs calibrated against experimental results reproduced the beam-to-column joints response [13]. The results of coupon tests provided the steel material properties.

Non-linear pushover step-by-step analyses have been performed by considering both geometrical and material non-linearities. Numerical and experimental results are compared in Fig. 11: a satisfactory agreement can be noted.

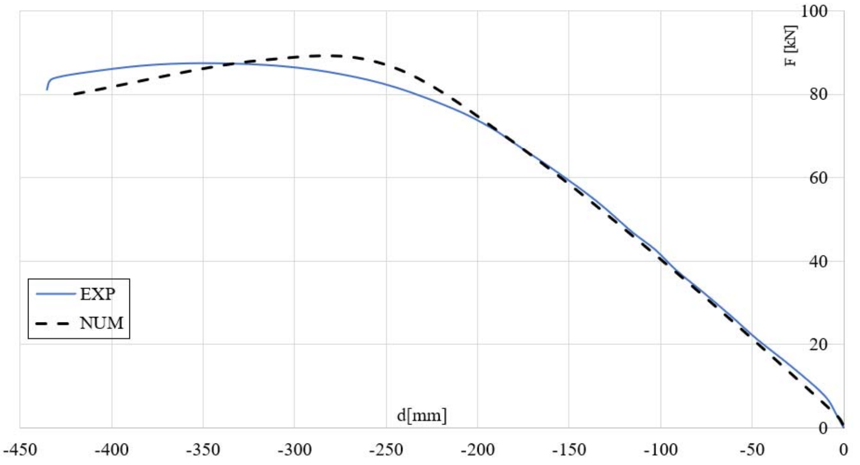


**Fig. 11.** Experimental vs. numerical results, frame with vertical load of 80kN.

## 6 Concluding Remarks

A study of the seismic response of steel storage pallet racks is presented in this paper. Collapses of racks recently happened stressed the need of an in-depth investigation at both the components and the full-scale level. Two push-over tests on a commercial two-bay four-level commercial rack were performed via an innovative testing set-up, which allows applying both vertical and horizontal loads. The tests were performed considering two different levels of the vertical loads, stressing the remarkable influence of such a parameter on the push-over test results. Reliable FE models were developed and calibrated against the experimental results, pointing out the importance of the adoption of the ‘design by testing’ approach. Further tests are planned for the near future.

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