Thin-Walled Structures 108 (2016) 391–405

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Experimental assessment of the seismic behavior of unbraced steel storage pallet racks

Alper Kanyilmaz*, Carlo Andrea Castiglioni, Giovanni Brambilla, Gian Paolo Chiarelli

Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, Italy

A R T I C L E   I N F O

Article history:
Received 9 December 2015
Received in revised form
18 August 2016
Accepted 2 September 2016
Available online 16 September 2016

Keywords:
Steel storage racks
Full scale tests,
Soft storey mechanism,
Global ductility of thin walled racking systems

A B S T R A C T

Steel storage racks are typically made of thin-walled cold formed steel profiles, which prove to be the most versatile, economic and sustainable elements for industrial rack construction. Their lightweight structural systems are usually designed to resist heavy load units, reaching considerable heights. However, the global behavior of storage racks under seismic actions is much less predictable than the behavior of steel buildings made of standard steel profiles and connections, mainly due to the perforations in their thin walled upright columns, and their semi-rigid beam-column and base plate joints. Full scale experimental investigations are greatly needed in order to understand and quantify the global performance of storage racks, and improve their design for seismic actions.

For the first time in Europe, thanks to the funding provided by Research Fund for Coal and Steel (RFCS), an extensive full-scale push-over testing program has been carried out on 8 fully-loaded pallet racking specimens (4 unbraced and 4 braced racks), provided by 4 different international rack producers.

This paper presents the experimental results of full scale push-over tests performed in the down-aisle (longitudinal) direction on fully-loaded *unbraced* specimens. In particular, experimental global capacity curves of the tested specimens are presented, discussing the key factors influencing the racks' response, as well as the failure mechanisms of the different rack typologies. Furthermore, the behavior factor (q) values of each specimen are derived from re-analysis of the test results. Vulnerability of unbraced racks to soft-storey mechanism is demonstrated, highlighting its causes. Design guidelines are provided in order to guarantee a globally homogenous ductility under seismic actions, along with the new safety requirements for the design of the floor connections of unbraced racks.

1. Introduction

Steel storage racks are commonly used to store goods in warehouses. Their structural components are often made of thin walled perforated profiles to ensure modularity, adaptability and versatility needed in storing goods. Due to the high competitiveness of the logistics industry, they are designed as lightweight as possible to save on steel material costs. Despite the lightness of their structural systems, storage racks carry very high unit loads (an average 8–10 kN per pallet), by far higher than their self-weight, contrary to typical loading in usual civil engineering structures.

Structural system of racks (Fig. 1) [1] is mainly composed of uprights (vertical members) made of perforated thin walled elements, and pallet beams (horizontal members), made of built-up closed sections linking adjacent frames, lying in the horizontal direction parallel to the operating aisle. Diagonal elements (bracings) connect the uprights to each other in the cross-aisle (transversal) direction to form the upright frames, whereas the connections between the uprights and the pallet beam (beam-to-column joints) in down-aisle (longitudinal) direction are usually made of proprietary hook-in connectors welded to the pallet beam ends, and engaged into perforated holes in the uprights. Uprights are connected to the industrial floor by L shaped components that are connected on the upright base on one leg, and on the floor on the other.

Stability of upright frames in cross-aisle direction is always provided by diagonal elements. On the other hand, in the down-aisle direction, rack designers usually prefer avoiding bracings to make the shelves accessible on both sides from two aisles, allowing an efficient loading and unloading of goods in service. Therefore in unbraced racks, stability to lateral loads in the longitudinal direction is provided by the semi-rigid beam-to-column joints and base plate connections. Bracings may also be used in the down-aisle direction if required, especially when high seismic

* Corresponding author.
E-mail address: alper.kanyilmaz@polimi.it (A. Kanyilmaz).

http://dx.doi.org/10.1016/j.tws.2016.09.001
0263-8231/

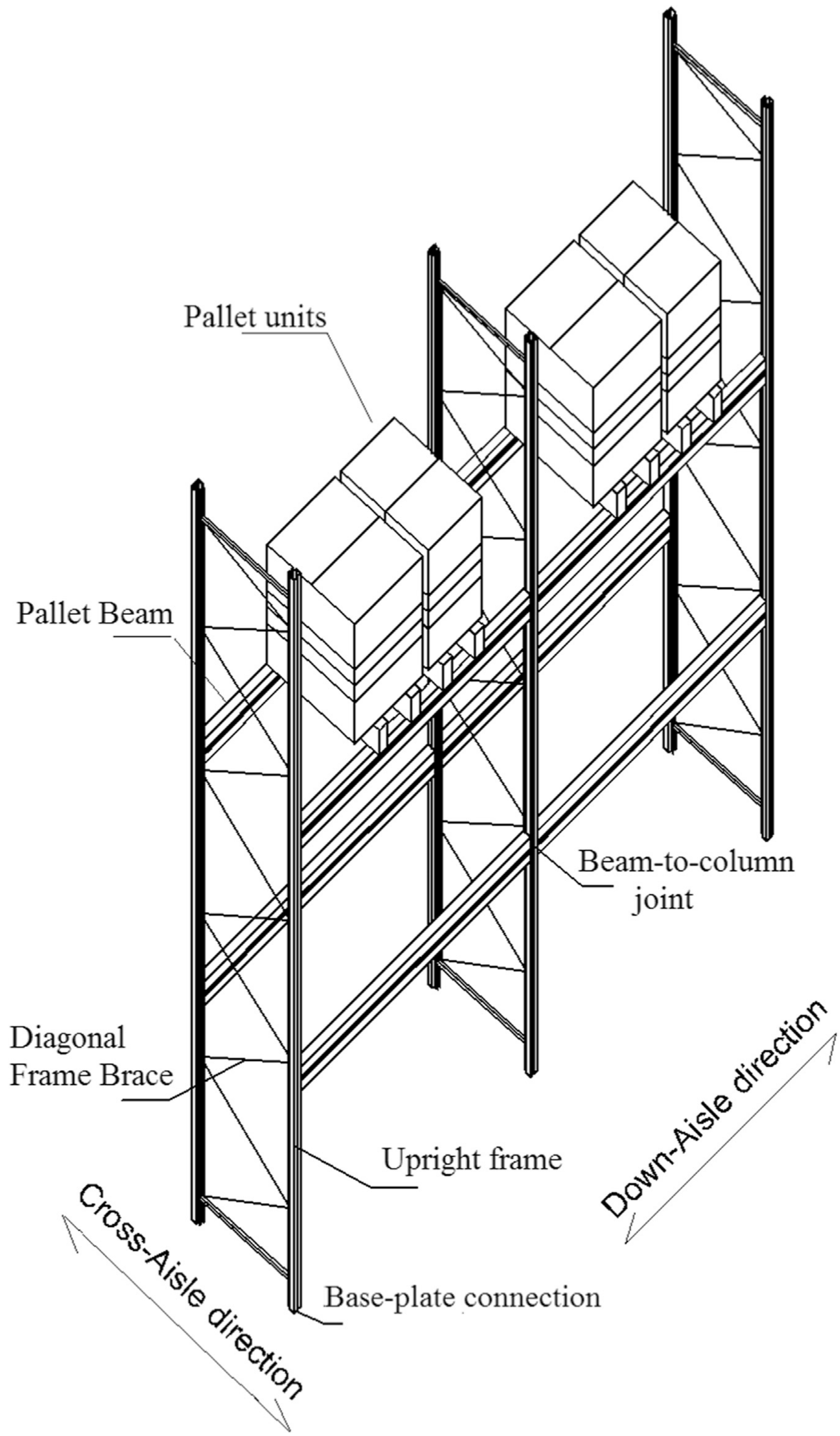

Fig. 1. Typical pallet rack configuration.

action is a concern. Different rack typologies are described by Pekoz et al. [2].

The design of storage racks is not a straight-forward task because of their peculiar structural forms, and difficulties predicting their structural behavior (both at global and local levels), which becomes even more complicated when storage racks are exposed to horizontal forces in seismic areas. Collapse of racks, during a seismic event, not only endangers the life of the employees and consumers (in case of "open to public" storage areas in shopping centers), but also results in a significant economic loss, much larger than the cost of the rack structure itself. Some examples observed after the recent Emilia-Romagna Earthquake (2012) are shown in Fig. 2 [3]. Picture a. shows the situation in a cheese factory where the racks were toppled down due to the absence of floor-connections. This was a very common type of collapse causing a significant economic loss in the area. In general, it is estimated that 633,700 wheels of Parmigiano Reggiano and Grana Padano cheese were damaged by falling off factory racks, with an