Engineering Structures 123 (2016) 434–450

Contents lists available at ScienceDirect

Engineering Structures

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

Influence of floor deflections on the performance of steel storage pallet racks

Claudio Bernuzzi, Damiano Persico, Marco Simoncelli *

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

A R T I C L E I N F O

Article history:
Received 30 August 2015
Revised 24 March 2016
Accepted 29 March 2016
Available online 13 June 2016

Keywords:
Steel storage pallet racks
Flexible/rigid floor slab
Structural analysis
Differential settlements
Design approaches
Load-carrying capacity

A B S T R A C T

One of the most important applications of thin-walled cold-formed elements is for the fabrication of selective steel storage pallet racks used to store goods. From the structural point of view, these systems are generally unbraced in the longitudinal direction and braced in the transversal direction. Recently, pallet rack provisions have been significantly improved, especially for what concerns design assisted by testing; however, further key aspects of relevance for structural design need urgent attention. Among them, it is worth mentioning the interaction between the racks and the supporting surfaces (i.e. foundations or floor slabs), which is expected to have a non-negligible influence in routine design, owing to the high degree of redundancy of the rack skeleton frames.

This paper summarizes a study on the influence of floor displacements on the performance of medium-rise steel storage pallet racks. In order to propose a wide range of data of practical interest for routine design, the effective load-carrying capacity has been evaluated by varying the position of the rack on the floor slab, the rack geometry, the ratio between the floor span and the rack length and the degree of rotational stiffness of both beam-to-column joints and base-plate connections. Moreover, a suitable equation, which is independent of the adopted design approach, is proposed to estimate the reduction of the performance with respect to the ideal case of racks supported by a rigid floor slab. Validation of the equation is carried out using design cases that are significantly different from those used for its calibration. Finally, Appendix A proposes complete design examples detailing the main calculations necessary to predict the reduction of the load carrying capacity associated with the floor slab deflection.

1. Introduction

Goods and products are generally stored in industrial framed systems (racks) made up of thin-walled cold-formed members, which represent the best solution from the logistic and economic points of view, owing to their high strength-to-weight ratio [1,2]. Depending on the storage density needs, in-service accessibility and picking modalities, several types of commercial racks are available on the market: the most common are pallet racks (Fig. 1), on which the present paper is focused. These structures, are generally comprised of a set of two vertical columns (uprights) connected to each other via lacings to form trusses (built-up laced) members, identified as upright frames, which are placed in the cross-aisle (transverse) direction. Storage units are supported by pairs of parallel pallet beams attached to two sub-sequent upright frames and the access is in the down-aisle (longitudinal) direction, where in general the vertical bracing elements cannot be placed because of the need to provide the maximum number of available pallet locations. From the structural point of view, racks are braced in the cross-aisle direction while they have to be considered semi-continuous unbraced frames [3] in the down-aisle direction, where stability to lateral loads is provided solely by the degree of flexural stiffness of the beam-to-column joints and base-plate connections.

Pallet rack design is carried out with reference to provisions quite recently updated in Europe [4–6], United States [7,8] and Australia [9]. Nevertheless, several aspects playing a key role in the design need additional investigation: one of them is the effective load carrying capacity when vertical displacements occur at upright bases supported by flexible foundations or deformable floor slabs. Due to the high redundancy of the structural system, differential settlements are expected to have a non-negligible influence on the rack performance but code requirements related to the rack-base interaction are extremely poor. The building skeleton frame is designed to meet the limitations given by the reference building codes, often before defining accurately the designated usage of the floors; in some instances, owner needs might change in terms of location of the storage areas inside the building or of weight or sizes of the stored pallet units. Generally

* Corresponding author.
E-mail address: marco.simoncelli@polimi.it (M. Simoncelli).

http://dx.doi.org/10.1016/j.engstruct.2016.03.066
0141-0296/

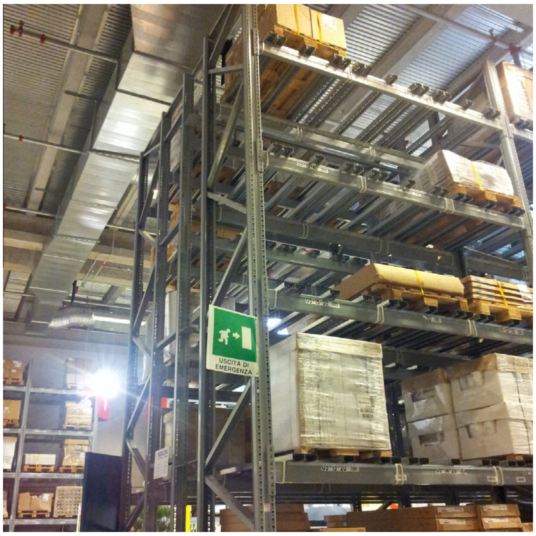

Fig. 1. Typical adjustable steel storage pallet-racks.

there is no interaction between the structural building designer and the rack manufacturing engineer: the former guarantees that the floor slab is adequate to support in-service the fully loaded storage system and the latter proposes the most convenient commercial solution, independent of the boundary conditions at the upright bases. It is always assumed that racks are connected to rigid floor slabs, without any attention to the effective interaction between the floor deflections and the storage system, thus neglecting the associated increments of the design set of horizontal displacements, internal forces and moments.

A research project is currently in progress at the Politecnico di Milano on the influence of the base deflections on the performance of industrial systems to store products and goods. The first phase, which is herein discussed, has been focused on pallet racks supported by floor slabs. For the sake of simplicity, it has been decided to make reference to bi-symmetric cross-section uprights: as a consequence, the important effects associated with warping torsion, Wagner coefficients and non-coincidence between the shear center and the cross-section centroid [10,11] have been neglected, owing to the need to reduce the number of parameters affecting research outcomes. A numerical analysis has been developed and summarized with reference to cases differing for the location of the racks on the floor slab, geometry of the racks and their components and degree of flexural continuity associated with beam-to-column joints and base-plate connections. The direct evaluation of the reduction of the load carrying capacity due to vertical deflections of the floor has been based on the cases of rigid and deformed floor slab and the associated design calculations have been developed with reference to two different European design procedures. Furthermore, an approximate equation is proposed for the direct assessment of the reduction of the rack performance and its validation is presented with reference to a second set of pallet racks, significantly different from those used for the calibration phase. Finally, Appendix A presents a complete design case where the reduced performance is appraised via numerical analyses as well as by means of the proposed design equation.

2. Standard provisions and rack base movements

Rack systems with height lower than 15–20 m are usually located inside independent industrial or commercial buildings; otherwise, for increased storage height (up to approximately 50 m [12]), rack warehouses (i.e. cladding racks), loaded also by wind and snow effects, are a convenient solution. Furthermore, racks having height up to 6–8 m and with a limited number of bays, instead of being placed on a concrete industrial pavement at the ground level are frequently located inside multi-storey buildings, directly supported by the floor slab, which is the case considered herein.

As to the design strategy, it is worth mentioning that building designers guarantee that all structural components fulfill the provisions requirements. Great attention is hence usually paid to the floor deflections, which have to be limited in-service to ensure they do not affect appearance, the comfort of users, functionality or eventual damage caused to finishes and/or to non-structural members. The current version of the European design provisions for concrete [13], steel [14] and steel–concrete composite [15] structures do not report any practical indications related to the deflection limits, which should always be specified by clients or could be obtained from the National Annex developed by each EU country to complete Eurocode requirements. General design principles are reported in Annex A of EN 1990 provisions (Basis of design) [16], but no values are directly proposed for limiting the vertical beam and slab deflection. From an engineering point of view, it seems however reasonable to make reference to the deflection limits proposed in the previous preliminary versions (ENV) of the European building provisions [17–19]. In the present research, the serviceability deflection limit for variable loads has been set at $L_{FS}/300$, where L_{FS} is the length of the floor slab assumed to be simply supported. No attention is paid to the total slab deflection due to permanent load, owing to the need to focus attention on the slab-rack interaction and to the very limited weight of the racks without pallet units, i.e. in the unloaded condition.

As already shortly discussed, the most common contractual situation is that the client/owner decides to locate the medium-rise pallet rack on an intermediate floor, without additional structural checks on the adequacy of the supporting floor slab loaded by the in-service rack. Usually, buildings are in fact designed and erected without any interaction between its designer and the rack manufacture engineer, despite the fact that the EN 15512 code [4] states that the limiting deflection values have to be agreed with the client/owner, taking into account the specific requirements of the installation. Otherwise, limit in-service values are recommended only for pallet beams in terms of vertical deflection as well as of twist angle when the load is not applied on the shear center of the cross-section. It seems that an adequate attention is paid to the floor tolerances and deformations: clause 5.1.5 declares that the flatness deviations and deformations of the building floor upon where the rack should be installed may be ignored when the building floor is designed in accordance with the relevant limit values specified in EN 15620 [20]. Clause 7.3.1 of that code is the sole part dealing with the slab deformations due to slab deflection but no useful indications are provided to designers and it is declared that:

- deflection of the floor slab results in additional stresses and inclination of the rack structure and can be considerable;
- deflection of the floor slab shall be included at the planning stage and information shall be provided by the specifier or client to the racking supplier for evaluation of the additional stresses in the racking;
- deflection of the floor slab shall be included at the planning stage by the specifier or client and added to the clearances and deformations as required for the specific project.

As an alternative, the floor slab could be treated as quasi-rigid, which implies that the deformations of the floor slab do not affect the structural behavior (deformations and stresses) of the rack, if the following assumptions are fulfilled: