



Performance of mono-symmetric upright pallet racks under slab deflections



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ABSTRACT

Goods and products are often stored in framed systems, such as pallet racks, which are used for industrial and commercial activities. Recently, pallet rack provisions have been significantly improved but there are still relevant aspects that need urgent attention for guaranteeing safe structural design. Among them, the interaction between the rack and the supporting surface (i.e. concrete foundation or floor slab) plays a non-negligible influence in routine design, owing to the high degree of redundancy of the skeleton frames. In addition, rack design is usually carried out using analysis packages unable to capture the behaviour of mono-symmetric cross-section members and hence all the warping effects are generally ignored.

This paper summarizes a study on the influence of floor displacements on the performance of medium-rise steel storage pallet racks. In order to obtain a reasonably wide range of data of practical interest for routine design, numerical analyses have been carried out by varying several key parameters such as the position of the rack on the floor slab, the rack geometry, the floor span length and the degree of rotational stiffness of both beam-to-column and base-plate connections. Moreover, attention has been focused on the influence of the accuracy of the structural model used in the design and two commercial analysis packages, differing for the degree of refinement of the implemented finite element *beam* formulation, have been considered. Finally, a suitable equation is presented to estimate the reduction of performance with respect to the ideal case of racks supported by rigid floor slab.

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1. Introduction

Goods and products are generally stored in industrial framed systems (racks) comprised of thin-walled cold-formed members, which represent the best solution from the logistic and economic points of view, owing to the 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 of them are the so-called selective pallet racks (Fig. 1), the focus of the present paper, which are characterized by having pallets that are always accessible, independent of the storage sequence.

These structures are generally comprised of a set of two vertical columns (uprights), often having mono-symmetric sections, that are connected to each other by means of lacings to form trussed (built-up laced) members. These are identified as upright frames, which are placed in the cross-aisle (transversal) direction. Stored units are supported by pairs of pallet beams that are attached to two adjacent upright frames and the pallet access is in the down-aisle (longitudinal)

direction, where in general the vertical bracings cannot be placed because of the need to optimise the number of pallet unit locations. From the structural point of view, racks are always braced in the cross-aisle direction. In the down-aisle direction they behave like semi-continuous unbraced (moment-resisting) frames [3], where stability to lateral loads is provided solely by the degree of flexural continuity associated with beam-to-column joints and base-plate connections.

Routine design is carried out with reference to recently updated provisions in Europe [4–6], the United States [7,8] and Australia [9]. Despite the recent updates, several aspects playing a key role in design need additional investigations and two of them, strictly related to each other, are considered in the present paper. The first is the assessment of the effective load carrying capacity if vertical displacements occur at the upright bases. In the case of flexible foundations or deformable floor slabs, due to the high redundancy of framed systems, the relative settlements are expected to have a non-negligible influence on the rack performance, but code requirements dealing with the rack-base interaction are either lacking or extremely poor. The second aspect needing urgent attention is related to the approaches used for routine design, which are inadequate for capturing actual rack response due to fact that they derive strictly from approaches proposed for carpentry steel frames, i.e. structural systems comprised of bi-symmetric cross-section members.

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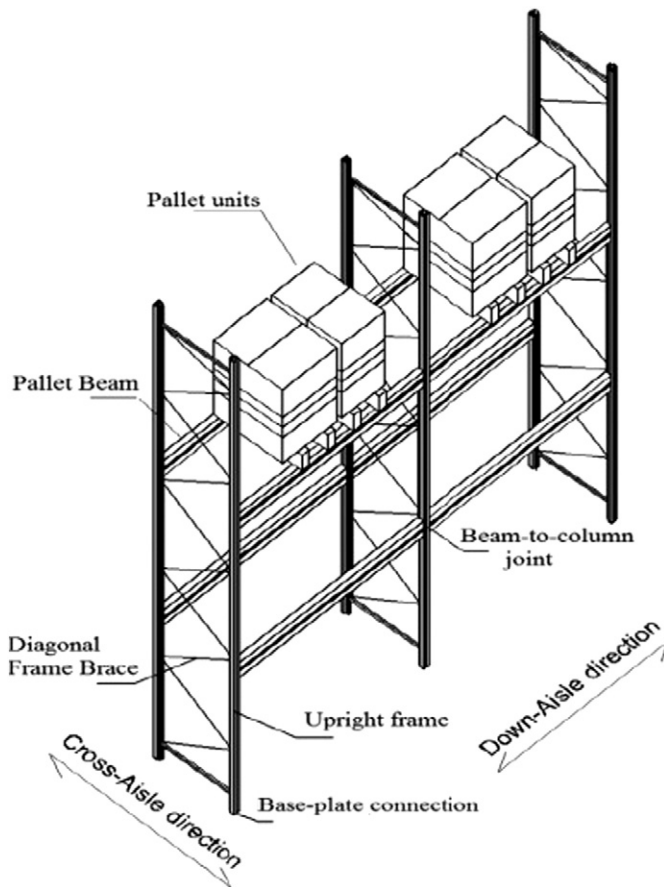


Fig. 1. Typical adjustable steel storage pallet-racks.

In a previous paper [10], the effect of the base displacement on the reduction of the pallet rack performance was discussed with reference to racks comprised of bi-symmetric cross-section uprights. Now, attention is focussed on racks with mono-symmetric uprights whose behaviour is significantly affected by warping torsion, Wagner coefficients and the non-coincidence between the shear centre and the cross-section centroid, as shown by Teh et al. [11]. Despite the relevant studies carried out on storage rack systems in the last years, in both numerical and experimental fields [12–21], these aspects are still neglected in the European routine design, leading in many cases to an overestimation of the rack performance [22]. The proposed research outcomes are based on a numerical parametric investigation, which has been developed based on cases differing in rack location on the floor slab, down-aisle rack layout, upright geometry and the 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 floor deflections has been based on the cases of rigid and deformed slabs. The associated design calculations have been developed with reference to two different European design procedures, with one leading to the most conservative evaluation of rack performance and the other leading to the least conservative [23,24]. Furthermore, two different FE beam formulations have been considered: the first is traditionally, but incorrectly, used by manufacturing engineers for rack design and the second is specifically developed for non bi-symmetric beams and hence adequate to investigate the behaviour of these structures. Finally, an approximate equation, suitably accounting for the presence of mono-symmetric cross-section uprights, is proposed for a direct assessment of the reduction of rack performance, which has been validated with reference to pallet racks that are significantly different from the ones adopted in the numerical analysis.

2. Standard provisions and rack base movements

The cases of interest considered herein, are representative of selective pallet racks having heights up to 6–8 m and with a limited number of bays, erected inside a multi-storey building and directly connected to the floor slab. Generally, these racks are located in areas where the public has access, such as supermarkets, discount stores and home handyman stores. A collapse could therefore result in the loss of stored goods, injuries and potentially the loss of human life. The most common contractual situation is that the clients and/or owners locate the rack on an intermediate floor, without any structural check regarding the adequacy of the supporting slab. Buildings are usually designed and erected without any interaction between the building designer and the rack manufacturing engineer, despite the fact that the EN15512 provisions [4] state that the limiting deflection values have to be agreed with the client/owner, taking into account the specific requirements related to the installation. Otherwise, in-service deformability values are specified only for pallet beams in terms of allowable vertical deflection and for twist angles when the load is not applied to the shear centre of the cross-section. Up to now, adequate attention does not seem to have been paid to the floor tolerances and deformations. These are covered by clause 5.1.5, which states 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 according to the relevant limit values specified in EN 15620 [25]. As to these guidelines, point 7.3.1 is the only part dealing with slab deformations due to settling and slab deflections due to vertical loads, but no useful indications are provided to the designers. It is stated that *deflection of the floor slab results in additional stresses and inclination of the rack structure and can be considerable*. Furthermore, the code also recommends that 1) *the 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* and 2) *the 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 its deformations never affect the set of displacements, internal forces and moments. As reported by the code, this can be assumed if the following conditions are satisfied:

- *the angular rotation at any location of the floor slab within the rack area shall not exceed 0.5 mrad;*
- *the overall vertical deformation shall not exceed 1/2000 of the total storage length;*
- *the overall vertical deformation shall not exceed 1/2000 of the total storage width.*

These statements rarely appear useful to manufacturing engineers from a practical point of view, which know only general data of the supporting surface, such as the floor span (L_{FS}). The limitation on the angular slab rotation implies an accurate knowledge of the response of the flooring system. Very complex activities should be made to evaluate correctly the floor displacement effects, on the rack internal forces and moments, especially in the case of existing buildings. As a practical result, these further structural checks could appear as complex and quite expensive if compared with the cost of the rack system itself and usually are never included in the design budget. Furthermore, it is clear that the condition of ‘quasi-rigid’ applied to the floor slabs of multi-storey buildings reflects a very severe design criterion associated with serviceability limit states. To satisfy this condition (limiting deflections to $L_{FS}/2000$) instead of the one [26] usually adopted for the floor slab in building design ($L_{FS}/300$) a significantly larger flexural stiffness (approximately at least 7 times) is required. This implies very thick, heavy and expensive slabs, needing for appropriate calculations, strictly depending on the selected rack layout. As an alternative, it seems more

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