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Influence of pallets on the behaviour and design of steel drive-in racks

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ABSTRACT

This paper analyses the influence of horizontal bracing restraints provided by the friction between pallet bases and rail beams on the static behaviour and design of steel drive-in storage racks. The pallet bracing restraints are shown to significantly influence the structural behaviour of the rack, and their effect on the bending moment distribution of the uprights is studied in the paper. The 2D single upright model proposed by Godley is improved in this study by including the restraints provided by the plan flexural stiffness of the rail beams and the friction between the pallets and rail beams. The improved 2D model was found to accurately reproduce the bending moment distributions obtained using 3D advanced finite element analysis. The 2D single upright model is used to analyse 36 drive-in racks under various load case combinations. The paper evaluates the influence of the pallet bracing restraints on the ultimate capacity of drive-in racks, clarifies the loading pattern(s) governing the structural design and determines the friction coefficient, or strength of a restraining device, required to prevent the pallets from sliding. It is shown that while restraints from pallets could potentially be considered in design, they would not lead to more economic structural solutions.

1. Introduction

Worldwide, steel storage racks are extensively used in the manufacturing, wholesale and retail industries to store goods. They are mostly freestanding structures and are often assembled from cold-formed steel profiles. Two main types of racks prevail, referred to as "selective racks" and "drive-in racks". In drive-in racks, pallets are stored on rail beams one after the other, and the forklift truck drives into the rack to store the pallets on the "first-in last-out" principle. The rail beams are offset from the centreline of the uprights so that the pallets apply both bending moments and axial compressive forces to the uprights. To allow the forklift truck passage, the rack is only braced horizontally at the top (plan bracing) and vertically at the back (spine bracing) in the down-aisle direction. Due to their floor space efficiency, drive-in racks are usually preferred to selective racks when storing the same goods with quick turnover, or in expensive storage spaces such as industrial freezers. Fig. 1 shows an example of a drive-in rack.

Experimental tests performed by Gilbert and Rasmussen [1] have shown that pallets act as horizontal braces between adjacent uprights, significantly influence the structural behaviour of drive-in racks and must be considered in order to accurately capture the 3D behaviour of drive-in racks. Similarly, earlier research by Salmon et. al. [2], who numerically investigated the buckling behaviour of symmetrically loaded drive-in racks by alternately considering and ignoring the pallet bracing restraints in the analysis, showed that pallet bracing restraints had significant influence on the non-sway buckling mode, although they had less influence on the sway buckling mode.

However, due to the uncertainty concerning the friction between the pallet bases and the rail beams, drive-in racks are currently designed without considering the bracing effects. If a device can prevent the pallets from sliding on the rail beams or if the coefficient of friction between the pallet bases and the rail beams can be reliably determined, the horizontal bracing effect provided by the pallets could be fully exploited in the design of a drive-in rack.

Hua and Rasmussen [3] measured the friction coefficient between wood pallets and rail beams and found that the average static friction coefficient between the rail beams and the pallet bases to be as high as 0.576, with a recommended design static friction coefficient of 0.439. This friction coefficient suggests that significant horizontal forces can develop between the pallets and the rail beams before sliding occurs, allowing the pallets to play a structural role in the behaviour of drive-in racks. It is noted, however, that this design static friction coefficient does not take into account grease or ice (in the case of industrial freezers) that may accumulate on rail beams.

Another aspect related to pallet bracing restraints is the in-plane shear stiffness of the pallet base. Hua and Rasmussen [3] experimentally found that the in-plane shear stiffness of pallet bases ranged from 5.1 N/mm to 31.4 N/mm, depending on the pallet condition. Characteristic design shear stiffness values of 3.9 N/mm for pallets deemed in poor condition and 8.3 N/mm for pallets deemed in good condition were recommended.

The current paper analyses the influence of the horizontal bracing effect of pallets on the static behaviour and design of steel drive-in

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Notations

A_u	Cross-sectional area of upright members
C_b	Coefficient depending on the BMD in the unbraced segment
E	Steel Young's modulus
f	Out-of-plumb load applied to a rail beam
$f_{u,m}$	Load applied in the translational stiffness $K_{uh,m}$
f_{oy}, f_{oz}	Elastic buckling stresses about the y- and z- axes
h, h_p	Frame bracing pitch
h_{rail}	Rail beam elevation
H	Height of the rack
I_u	Second moment of area of the upright
I_r	Second moment of area of two rail beams.
k_u	Upright stiffness
K_b	Top rotational stiffness of the upright for a rack is sway mode
K_c	Base plate rotational stiffness of the base plate to floor connection
$K_{r,i}$	Rail beam translation stiffness at rail beam elevation i
K_t	Top translational stiffness for the single upright model
K_{uh}	Horizontal translational stiffness of the upright at the point of application of load P
$K_{uh,m}$	Horizontal translational stiffness of the inner uprights
$K_{uh,fb}$	Horizontal translational stiffness of the front and back uprights
l_{ex}, l_{ey}, l_{ez}	Effective buckling lengths about the x-, y- and z- axes, respectively
L	Distance between two uprights (upright frame width)
N^*	Design factored axial load
N_c	Nominal axial compression capacity of the upright
N_{cd}	Nominal axial compression distortional capacity of the upright
N_{cl}	Nominal axial compression local capacity of the upright
N_{ce}	Nominal axial compression global capacity of the upright
N_{crb}	Elastic buckling load of the upright determined from an elastic buckling analysis
N_s	Number of rail beam elevations
N_u	Number of uprights in the down-aisle direction
M_{bx}, M_{by}	Nominal bending moments capacity of the upright about the x- and y-axes, respectively.
M_{bxd}	Nominal distortional bending moment capacity of the upright about the x-axis
M_{bxl}	Nominal local bending moment capacity of the upright about the x-axis
M_{bxe}	Nominal global bending moment capacity of the upright about the x-axis
M_o	Global buckling moment
M_x^*, M_y^*	Design factored bending moments about the x- and y-axes, respectively
P	Horizontal load applied to the upright.
P_b, P_c	Load
s	Friction effect
S_f	Friction force
r_{ol}	Radius of gyration
W	Pallet load
α	Out-of-plumb angle
Δ	Total down-aisle displacement at the top of a drive-in rack
Φ_b	Reduction capacity factor for member in bending
Φ_c	Reduction capacity factor for member in compression
ω	Pallet uniform distributed load
μ	Friction coefficient

racks in the down-aisle direction only, as due to the upright frames, pallets are not believed to influence the behaviour of drive-in racks in the cross-aisle direction. It should also be noted that the friction between pallet bases and the rail beams would prevent the pallets from dropping through on account of the upright bowing deformations [4,5]. As such, the serviceability check against upright bowing deformations is not considered in this paper.

The 2D analysis model for drive-in racks proposed by Godley [6] is improved herein by introducing the horizontal restraints provided by both the rail beams and the pallet bracing restraints. The improved model is checked against the 3D model developed by Gilbert and Rasmussen [1,7] that is calibrated against laboratory test results. The influence of the pallet restraints on the bending moment distribution in the uprights is also evaluated. Thirty six drive-in racks representing the global sale of an Australian manufacturer over three years are then analysed using the improved 2D model under all possible static loading scenarios, alternately considering and ignoring the pallet bracing restraints. This paper evaluates the influence of pallet bracing restraints on the ultimate capacity of steel drive-in racks in the down-aisle direction, clarifies the loading scenario(s) governing the design and determines the friction coefficient or the strength of a restraining device required to prevent the pallets from sliding.

2. Single upright model

2.1. Single upright model proposed by Godley

In order to reduce the computation time associated with large models, Godley [6] developed a "single upright model" to analyse fully loaded drive-in racks in the down-aisle direction. The upright is restrained at its base by a spring support having a rotational stiffness Kc, and at its top by another having a rotational stiffness Kb and a translational stiffness Kt, as shown in Fig. 2. Kc represents the restraint provided by the base plate to the floor connection, Kb the restraint provided by the portal beams in double curvature (sway mode) having semi-rigid connections to the upright, and Kt the combined restraint from the plan bracing (spanning the entire rack), spine bracing (spanning one bay) and upright frames. Pallet loads and out-of-plumb loads are applied to the upright as shown in Fig. 2, where the rack is assumed to be fully loaded such that loads W are applied on all rail beams. Detailed calculations for Kc, Kb and Kt, can be found in [6].

Despite its attractiveness, this model has limitations as it (i) ignores the restraint provided by the rail beams, (ii) does not take into account the horizontal bracing restraint provided by pallets, and (iii) does not consider all possible upright loading scenarios, including partially loaded racks where pallet loads are placed asymmetrically so as to induce bending of the upright. These limitations are addressed in following sections.

2.2. Improved single upright model

2.2.1. Rail beam restraints

Typically, the out-of-plumb of drive-in racks is modelled by horizontal forces at the rail beam supports that are linearly proportional to the gravity loads of the pallets (see Section 4.1.2). For a fully loaded rail beam, the front and the back uprights are less loaded than the inner uprights, resulting in smaller out-of-plumb forces being applied to the front and back uprights, as illustrated in Fig. 3 for a rack with two upright frames. Therefore and since rail beams link the uprights together, they restrain the deflection of the inner uprights when subjected to the out-of-plumb forces, as shown in Fig. 3(b), in which α is the out-of-plumb angle with vertical.

Consequently, these restraints provided by the rail beams are introduced into the single upright model by adding a horizontal translational stiffness $K_{r,i}$ at each rail beam elevation i, as shown in Fig. 4. An expression for $K_{r,i}$ is derived in Section 2.2.1.2.