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Load-level isolator model for pallets on industrial storage racks and validation with experimental results

Marcelo Sanhueza-Cartes[1], Nelson Maureira-Carsalade*[1], Eduardo Núñez[1] and Ángel Roco-Videla[2]

[1]*Facultad de Ingeniería, Universidad Católica de la Santísima Concepción, Concepción, Chile*
[2]*Universidad Arturo Prat, Iquique-Chile*

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Abstract. This paper introduces a system allows for seismic isolation of the pallet from the rack in the down-aisle direction, occupies minimal vertical space (5 cm) and ±7.5 cm of deformation range. A conceptual model of the isolation system is presented, leading to a constitutive equation governing its behavior. A first experimental campaign studying the response of the isolation system's components was conducted to calibrate the parameters of its constitutive equation. A second experimental campaign evaluated the response of the isolation system with mass placed on it, subjected to cyclic loading. The results of this second campaign were compared with the numerical predictions using the pre-calibrated constitutive equation, allowing a double-blind validation of the constitutive equation of the isolation system. Finally, a numerical evaluation of the isolation system subjected to a synthetic earthquake of one component. This evaluation allowed verifying attributes of the proposed isolation system, such as its self-centering capacity and its effectiveness in reducing the absolute acceleration of the isolated mass and the shear load transmitted to the supporting beams of the rack.

Keywords: constitutive numerical model; double-blind validation; down-aisle direction; experimental tests; pallet isolation

1. Introduction

Industrial storage racks are among the most vulnerable structures system against seismic action (Beattie, 2006). This has been evident during recent earthquakes, such as the Darfield earthquake that occurred in September 2010 in the city of Christchurch (Crosier *et al*. 2010). During an inspection conducted by a group of researchers from the USA and New Zealand in various industrial buildings, damages that varied from moderate to total collapse were identified in industrial storage racks. These results are consistent with the findings of Uma and Beattie (2011) and Clifton *et al*. (2011), who reported observing severe damage to this type of structure as well as storage losses. On the other hand, Perrone *et al*. (2019) conducted a study on the seismic behavior of non-structural elements during the 2016 Central Italy earthquake. They observed severe damage to industrial storage racks, primarily due to overturning and buckling of the columns. According to Miranda *et al*. (2012), during the 2010 Maule-Chile earthquake, considerable damage was also identified in Chilean industrial storage racks. Rossi *et al* (2019) mention that the inadequate seismic performance of this type of structures is mainly due to the lack of detailing in its general design and connections to support lateral forces.

Currently, industrial storage racks are growingly in demand due to the rise in e-commerce and the growth of the logistics sector (Donà *et al*. 2022). These structures are increasingly used in commercial spaces and open to the public, so a structural failure and even the fall of pallets represents a potential danger for clients and workers (Alhan and Gavin 2005, FEMA 460 2005, Sideris *et al*. 2010). Due to the different problems that racks have faced during seismic events, different effects have been produced in the industry, such as: monetary losses, human losses and indirect losses due to business interruption (Brown *et al*. 2015, Donà *et al*. 2019). Some authors have proposed mitigation solutions to reduce lateral accelerations in industrial storage racks due to seismic loading, in addition to proposals to improve their performance and safety in general (Donà *et al*. 2022). These mitigation solutions are mainly based on passive type seismic protection systems, such as energy dissipation, tuned mass dampers and seismic isolation. When implementing any of these technologies, there is also an increase in the cost of the rack. Regarding this, Kilar *et al.* (2013), evaluated the economic feasibility of implementing seismic isolation to an industrial storage rack. They obtained that for ground motion intensities ranging from low to moderate, when only a repair of the structure is required, the retrofit using such technology is not economically viable. While, for higher intensities of earthquakes, when there is an interruption of the business activity due to rack damage, falling merchandise or collapse of the rack in general, the implementation of this type of technology could be of great benefit.

Among the specific energy dissipation devices to protect industrial storage racks is the base plate - column connection proposed by Tang *et al.* (2017). This proposal consists of the insertion of a steel sliding friction plate

*Corresponding author, Ph.D.
E-mail: nmaureira@ucsc.cl

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Nomenclature

a: vertical distance between the upper damper support and its lower support (cm).
b: horizontal distance between the upper damper support and the lower support (cm).
b_a: inner width of the insulation platform (cm).
b_t: external width of the isolation platform (cm).
L_a: length of isolation platform (cm).
L_t: length of isolation platform plus the safety distance (cm).
d: diagonal distance between the upper damper support and the lower support (cm).
F_I: inertial force (N).
F_r: friction force (N).
F_N: normal force (N).
F_{Di}: dissipater force of i-th damper.
F_{Ei}: elastic force of i-th spring.
P: weight on the isolation system (N).
v: displacement of the local degree of freedom (mm).
$\dot{v}$: velocity of the local degree of freedom (cm/s).
v_0: precompression displacement of springs in the local degree of freedom (cm).
u: displacement of the global degree of freedom (cm).
$\dot{u}$: speed of the global degree of freedom (cm/s).
$\ddot{u}$: relative acceleration with respect to the ground (cm/s^2).
θ: angle formed as a result of the vertical misalignment between the upper and lower supports of the springs parallel to the shock absorbers.
m: total mass (platform + pallets) (kg).
g: gravitational acceleration (9.81 m/s^2).
μ_{eq}: equivalent coefficient of friction.
$\overline{\mu}_{eq}$: average equivalent coefficient of friction.
$\bar{E}_d$: average energy dissipated per cycle (J).
$\overline{E}_d^{(Ex.)}$: average dissipated energy per cycle obtained experimentally (J).
$\overline{E}_d^{(\mathrm{A.M.})}$: average dissipated energy per cycle obtained using the analytical model (J).
$k_s^{(A)}$: theoretical stiffness of springs (N/cm).
$k_s^{(E)}$: experimental stiffness of springs (N/cm).
T_I: isolation period (s).
d_w: wire diameter (mm).
D: mean diameter of the spring (mm).
G: shear modulus of steel (MPa).
N_a: number of active coils of springs.
N_c: number of charge-discharge cycles of the forcing.
ε_F: relative error between exp. and analytical spring stiffness.
F_v: force of the local degree of freedom of the damper.
F_u: force of the overall degree of freedom of the damper.
β: angle formed due to the vertical misalignment between the upper and lower supports of the shock absorbers.
$\overline{F}_{t,c}^{max}$: maximum compression and traction force of the shock absorbers.
f_{ai}: auxiliary function used for the analytical model.
ε_{E_d}: relative error between experimental and analytical dissipated energy.
ε_F: relative error between experimental and analytical force.
$\ddot{u}_g$: Ground acceleration (input).
$u_{g,max}^{(abs.)}$: maximum absolute ground displacement
$\ddot{u}_{g,max}^{(abs.)}$: maximum absolute ground acceleration
$u_{max}^{(rel.)}$: maximum relative pallet-rack displacement
$\ddot{u}_{max}^{(abs.)}$: maximum absolute pallet-rack acceleration
$Q_{0,max}^{(I.S.)}(m)$: max. shear load of pallet with mass m isolated.
$Q_{0,max}^{(fixed)}(full)$: max. pallet-rack shear load with full loading mass fixed to the rack.