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Experimental assessment of static friction between pallet and beams in racking systems

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ABSTRACT

In order to investigate the sliding behavior of pallets stored on steel racking systems, a large number of sliding tests under both static and dynamic conditions were performed within the EU-RFCS Research Project "SEISRACKS: Storage Racks in Seismic Areas". In this paper, the results obtained for the assessment of the Static Friction Factor between pallet and beams are described and commented upon.

1. Introduction

Despite their lightness, racking systems carry very high live load (many times larger than the dead load, opposite of what happens for usual civil engineering structures) and can raise a considerable height.

Racks are widely adopted in warehouses where they are loaded with tons of (more or less) valuable goods. The loss of these goods during an earthquake may represent, for the owner, a very large economic loss, much larger than the cost of the whole rack on which the goods are stored, or of the cost for its seismic upgrade. Racks are also more and more frequently adopted in supermarkets and shopping centers, in areas open to the public. The falling of the pallets, in this case, may endanger the life of the costumers as well as that of the workmen and employees. Sliding of the pallets on the racks and their consequent fall represents a limit state that might occur during a seismic event also in the case of a well designed storage rack, as the phenomenon depends only on the dynamic friction coefficient between the pallet and the steel beams of the rack. Besides the usual global and local collapse mechanisms, an additional limit state for the system is represented by the fall of the pallets with subsequent damage to goods, people and to the structure itself.

At present, there are technical limitations in the field of safety and design of storage racks in seismic areas: lack of knowledge on actions challenging the structures, lack of knowledge on structural behavior in terms of ductility and sliding conditions of the pallets on the racks and lack of Standard Design Codes in Europe. To solve some of these limitations, the EU sponsored through the Research Fund for Coal and Steel an RTD project titled "Storage Racks in Seismic Areas" (acronym SEISRACKS, Contract number: RFS-PR-03114), including an experimental research, presented hereafter on static and dynamic friction behavior of the coupling steel beam-wooden pallet, consisting in about 1260 static tests and 182 dynamic tests. This paper is focused only on the results of the static tests, considering the influence of different parameters (such as the type of pallet and beam, the stored mass and the mass eccentricity). Dynamic tests are presented in another paper.

Storage racks are composed of specially designed steel elements that permit easy installation and reconfiguration, consistent with the merchandising needs of a warehouse retail store. Except where adjacent to walls, storage racks normally are configured as two rows of racks that are interconnected. Pallets typically can have plan areas of approximately one square meter and can have a maximum loaded weight of approximately 10–15 kN. Storage rack bays are typically 1.0–1.1 m deep and 1.8–2.7 m wide and can accommodate two or three pallets. The overall height of pallet rack structural frames, found in retail warehouse stores, varies between 5 and 6 m. In industrial warehouse facilities, racking system can reach considerable heights, such as 12–15 m.

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The rack industry calls the longitudinal direction the down-aisle direction, and the transverse direction the cross-aisle direction. Proprietary moment connections are typically used as the structural system in the down-aisle direction and braced frames are typically used as the structural system in the cross-aisle direction.

2. Friction models

Friction is the tangential reaction force between two surfaces in contact. Physically these reaction forces are the results of many different mechanisms, which depend on contact geometry and typology, properties of the bulk and surface materials of the bodies, displacement and relative velocity of the bodies and presence of lubrication.

In dry sliding contacts between flat surfaces, friction can be modeled as elastic and plastic deformation forces of microscopic asperities in contact. For each asperity contact the tangential deformation is elastic until the applied shear pressure exceeds the shear strength τ_y of the surface materials, when it becomes plastic.

There are different models of friction that consider stationary condition, e.g. constant velocity of the contact surfaces, and other, developed in the last century, that consider friction with a dynamic model.

In the Coulomb [6] model, the main idea is that friction opposes motion and that its magnitude is independent of velocity and contact area (Fig. 2.1a). It can therefore be described as $F=F_C\ sgn(v)$, where the friction force F_C is proportional to the normal load, i.e. $F_C=\mu F_N$

The Coulomb [6] friction model does not specify the friction force for zero velocity. It may be zero or it can take any value in the interval between $-F_C$ and F_C, depending on how the sign function is defined.

This very simple model is often modified with the introduction of viscosity parameters in order to take into account a dependence on velocity, $F=(F_C+F_V\ v)sgn(v)$ as shown in Fig. 2.1b.

Stiction (Fig. 2.2a) is short for static friction as opposed to dynamic friction. It describes the friction force at rest. Morin [12] introduced the idea of a friction force at rest that is higher than the Coulomb friction level. Static friction counteracts external forces below a certain level and thus keeps an object from moving. It is hence clear that friction at rest cannot be described as a function of velocity only. Instead it has to be modeled using the external force F_E in the following way: $F=F_E$ if $v=0$ and $|F_E|< F_S$; $F=F_S\ sgn(F_E)$ if $v=0$ and $|F_E|\geq F_S$.

The friction force for zero velocity is a function of the external force and not of the velocity. The friction force does not decrease discontinuously as in Fig. 2.2a, but the velocity dependence is continuous as shown in Fig. 2.2b. This is called Stribeck friction.

A more general description of friction than the classical models is, therefore: $F=F(v)$ if $v\neq 0$; $F=F_E$ if $v=0$ and $|F_E|< F_S$; otherwise it is $F=F_S\ sgn(F_E)$; where $F(v)$ is an arbitrary function, which can be as in Fig. 2.3.

Function $F(v)$ is easily obtained by measuring the friction force for motions with constant velocity. The curve schematically shown in Fig. 2.2a, is often asymmetrical.

Other static models of friction, as Karnopp model [11] model and Armstrong's [1] model are described by Olsson et al. [13]. Lately there has been a significant interest in dynamic friction models that describe friction as a dynamic system, with differential equations. In the Dahl [7–9] model it is assumed that the friction force is only position dependent, i.e. it depends only on the relative displacement x of the two surfaces. The starting point of this model is the stress–strain curve of the classical solid-mechanics theory. When subjected to stress the friction force increases gradually until rupture occurs. Let x be the displacement, F the friction force and F_c the Coulomb friction force. Then, Dahl's model has the form:

$$\frac{dF}{dx}=\sigma\cdot\left(1-\frac{F}{F_C}\cdot\mathrm{sgn}(v)\right)^{\alpha}$$

where σ is the stiffness coefficient and α is a parameter that determines the shape of the stress–strain curve. The value $\alpha=1$ is commonly used, while higher values give a stress–strain curve with a sharper bend. Fig. 2.3 shows a graphical representation of this model.

This model is a generalization of the Coulomb model, but it doesn't include the Stribeck effect, which is a rate dependent phenomenon, and does not capture stiction.

Various other dynamic models, generally complex and not described herein, are indicated in bibliography. There are among them that developed by Bliman and Sorine [2–4] based on the experimental investigations of Rabinowicz [14], and another important recent dynamic model, the LuGre Model (Canudas de Wit et al. 1995).

For the assessment of the sliding of pallets on racks, instead of adopting « a priori » one of these models, as it cannot be stated which one fits better the real behavior, it was decided to describe the phenomenon by means of a numerical analysis. Particularly for the sliding of pallets on rack systems, a numerical model was developed within the SEISRACKS project by Denoël and Degée [10], considering a SDOF sliding system subjected to a sinusoidal ground motion $u(t)$ reported in the references.

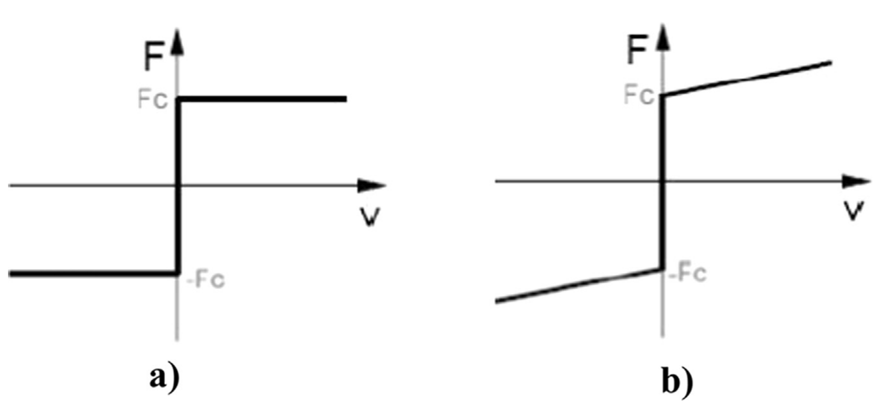

Fig. 2.1. (a) Coulomb friction model, (b) Coulomb friction model with the adding of viscosity.