STATIC AND DYNAMIC FRICTION BEHAVIOUR TESTS FOR STEEL STORAGE RACKING SYSTEMS: STATIC PROPERTIES

Carlo A. Castiglioni, Alberto Drei,, Alper Kanyilmaz
Politecnico di Milano
ABC Department, Architecture, Built Environment and Construction Engineering
Milano, Italy
carlo.castiglioni@polimi.it, alberto.drei@polimi.it

Panayotis Carydis, Harris Mouzakis
National Technical University
Laboratory of Earthquake Engineering
Athens, Greece
pkary@tee.gr

ABSTRACT

A quite large series of tests on the static and dynamic friction properties of steel storage racking systems were performed within the project titled "Storage Racks in Seismic Areas" (acronym SEISRACKS) sponsored by the EU, Research Fund for Coal and Steel. In this paper are described the results obtained for the assessment of the static friction properties of the pallet-beam systems. The dynamic aspects will be treated in a further paper.

SOMMARIO

Nell'ambito del progetto "Storage Racks in Seismic Areas" (acronimo SEISRACKS) promosso dalla UE, Research Fund for Coal and Steel, è stata svolta una serie di prove per la determinazione delle proprietà di attrito statico e dinamico fra pallet e travi di scaffalature metalliche. In questo articolo sono illustrate le prove relative all'attrito statico, rimandando ad altra nota la presentazione delle prove dinamiche.

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. Due to their peculiarities, additional modeling and design rules are required for these non-traditional steel structures, with particular attention for storage racks installed in a seismic zone, where they must be able to withstand dynamic forces. Racks, widely adopted in warehouses, are usually loaded with tons of (more or less) valuable goods. The loss of these goods during an earthquake may represent 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. Moreover, as they are frequently adopted in supermarkets and shopping centres, the falling of the pallets may endanger the life of people inside. 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 friction behavior between the pallet and the steel beams of the rack. At present, there is some lack of knowledge on the structural behavior and sliding conditions of the pallets. To solve part of these limitations, the EU sponsored, some years ago, an RTD project titled "Storage Racks in Seismic Areas" (acronym SEISRACKS), which promoted the research presented.

Storage racks are composed of specially designed steel elements that permit easy installation and reconfiguration. Except where adjacent to walls, storage racks normally are configured as two interconnected rows of racks. 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 in retail warehouse stores, varies between 5 and 6 meters. In industrial warehouse facilities, racking system can reach considerable heights, such as 12-15 meters. The rack industry calls the longitudinal direction the down-aisle direction, and the transverse direction the cross-aisle direction. The structural systems typically adopted are proprietary moment connections in the down-aisle direction, and braced frames in the cross-aisle direction.

2 FRICTION MODELS

Friction is the tangential reaction force between two surfaces in contact. Physically these reaction forces depend on contact geometry and typology, properties of the bulk and surface materials of the bodies, displacement and relative velocity of the bodies. There are different models of friction that consider stationary condition. In the Coulomb model (1776), the main idea is that friction opposes motion and that its magnitude is independent of velocity and contact area, where the friction force F_C is proportional to the normal load.

$$F = F_C \operatorname{sgn}(v) \qquad\qquad F_C = \mu \cdot F_N$$

This very simple model is often modified with the introduction of viscosity parameters in order to take into account a dependence on velocity, as shown in Figure 1, where is reported also *Stiction.* It indicates a friction force at rest, introduced by Morin (1833), that is higher than the Coulomb friction level.

b)

Fig.1: Coulomb friction model: a) with Stiction; b) with a continuous decrease of friction

Stribeck (1902) observed that the friction force does not decrease discontinuously as in Figure 1a, but that the velocity dependence is continuous as shown in Figure 1b. This is called Stribeck friction. Other quasi-static models of friction were developed in the following.

3 ASSESSMENT OF THE STATIC FRICTION FACTOR

About 1260 quasi-static sliding tests and 200 dynamic tests (not discussed in this paper) were carried out at the Laboratory for Earthquake Engineering (LEE) of the National Technical University of Athens (NTUA). The tests were aimed to obtain the static friction factor for different combinations of types of beams and pallets, and to study the influence of the mass and of its eccentricity. The test set-up, based on the principle of the inclined plane (Figure 2), consists of a rigid steel frame free to rotate about a pinned axis. Two horizontal beams are fixed on the frame. The axial distance between the pinned axis and the free edge of the frame is 1575 mm. One pallet, with a rigidly fixed mass of 8kN, is positioned on the beams. The system is gradually and slowly inclined with the use of a crane, that lifts the frame from its free edge, while the vertical displacement and the relative displacement between pallet and beam, are measured. Thirty repetitions of each test (combination of pallet and beam) were carried out. These tests were performed in down and cross-aisle direction.

Fig. 2: Experimental set-up for quasi-static sliding tests in cross-aisle direction

Three different values of the applied mass were considered (251 kg, 785 kg, 1036 kg) as well as the different position of the mass on the pallet (centred, eccentric downward, eccentric upward). Seven types of pallets and six types of beam, manufactured by three different companies, were used in the tests (some represented in Figures 3 and 4), with the following denomination:

Table 1: Type of pallet and beam used in the different tests

PALLETS	**BEAMS**
P1: Wooden Euro pallet 800x1200, new, dry	B1: Cold rolled, powder coated, new (Producer A)
P2: Wooden Euro pallet 800x1200, old, dry	B2: Cold rolled, hot dip coated, new (Producer A)
P3: Wooden Euro pallet 800x1200, old, wet	B3: Cold rolled, hot zinc coated, new (Producer A)
P4: Wooden American pallet, new, dry	B4: Cold rolled, hot dip coated, new (Producer B)
P5: Wooden American pallet, old, dry	B5: Cold rolled, hot dip coated, new (Producer C)
P6: Wooden American pallet, old, wet	B6: Cold rolled, hot dip coated, new (Producer C)
P7: Plastic Euro pallet	

a) b) c)

Fig. 3: a) Wooden Euro pallet, b) Wooden American, c) Plastic Euro pallet

Fig. 4: examples of beam sections: type B1, type B4 and type B6

Pallet P1 is a wooden Euro pallet, new and dry. Pallet P2, a wooden Euro pallet old and dry, takes into account pallet wearing. An old wooden Euro pallet spread with water for a few minutes before testing (pallet P3) simulates eventual environmental conditions. The same aspects were considered also for the American type of pallets, respectively P4, P5, and P6.
Pallet P7 is a plastic Euro pallet, now more and more adopted, as it is resistant and can be more easily cleaned than the wooden one.

4 STATIC FRICTION IN CROSS-AISLE DIRECTION

Sliding in cross-aisle direction is very dangerous because the pallet width is 1200 mm while the rack width is usually 1100 mm. Hence, a few mm of displacement, eventually correlated to a small eccentricity of positioning, can result in a loss of support of the pallet.
The following figures show the mean values of the static friction factor, for every test type. All the tests are repeated 30 times in the same conditions, and carried out with a mass of 785 kg centered on the pallet. The final table reports a statistical analysis of the experimental results, with Mean value μ, Standard deviation σ, Maximum and Minimum values,

$$Cov\% = \frac{\sigma}{\mu}\cdot 100 \quad \Delta^{+}\% = \frac{Max-\mu}{\mu}\cdot 100 \quad \Delta^{-}\% = \frac{\mu-Min}{\mu}\cdot 100 \quad \alpha^{+} = \frac{Max-\mu}{\sigma} \qquad \alpha^{-} = \frac{\mu-Min}{\sigma}$$

4.1 Influence of the pallet type and of the beam type

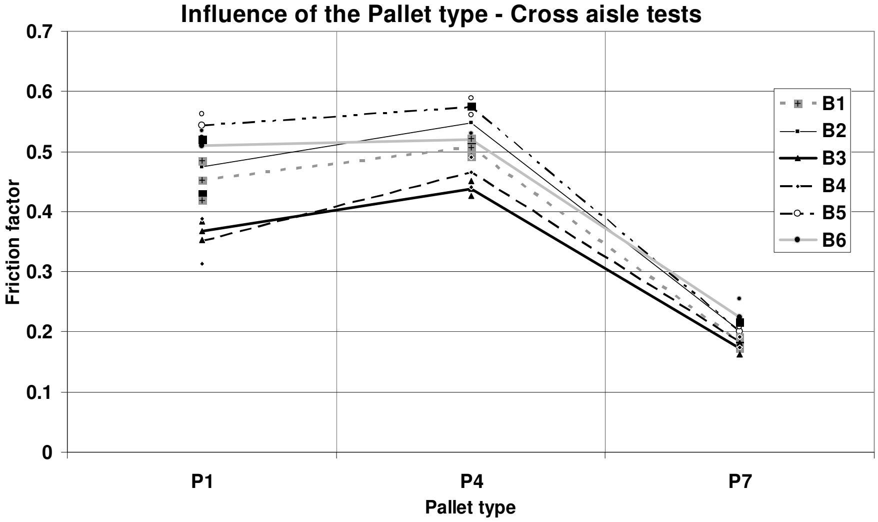


Fig. 5: Friction in cross-aisle direction: influence of pallet type for different types of beam

Figure 5 shows the influence of the pallet type on the static friction factor in cross-aisle direction, while 0 presents the statistics of the results.

The highest mean value of the friction factor (0.51) is that of Pallet P4 (American Wooden Pallet) while pallet P7 (Plastic Euro Pallet) has the lowest. Pallet P1 (Wooden Euro Pallet) has an intermediate value, very close to that measured for Pallet P4. Scatter of the data for all the pallets is limited, with *Cov.* ranging from 9.8% (P4) to 16.9% (P1), in particular P4 has the lowest scatter of the data, P1 has the highest one and P7 has an intermediate value.

Table 2: Statistics of test results for different types of pallet

	μ	σ	*Cov%*	*Max*	*Min*	Δ^+ %	Δ^- %	$\mu+\sigma$	$\mu-\sigma$	$\mu+2\sigma$	$\mu-2\sigma$	α^+	α^-
P1	0.45	0.08	16.9	0.58	0.27	28.7	39.7	0.53	0.37	0.60	0.30	1.70	2.35
P4	0.51	0.05	9.8	0.61	0.41	19.5	18.5	0.56	0.46	0.61	0.41	2.00	1.89
P7	0.19	0.02	11.8	0.34	0.16	72.9	19.6	0.22	0.17	0.24	0.15	6.18	1.66

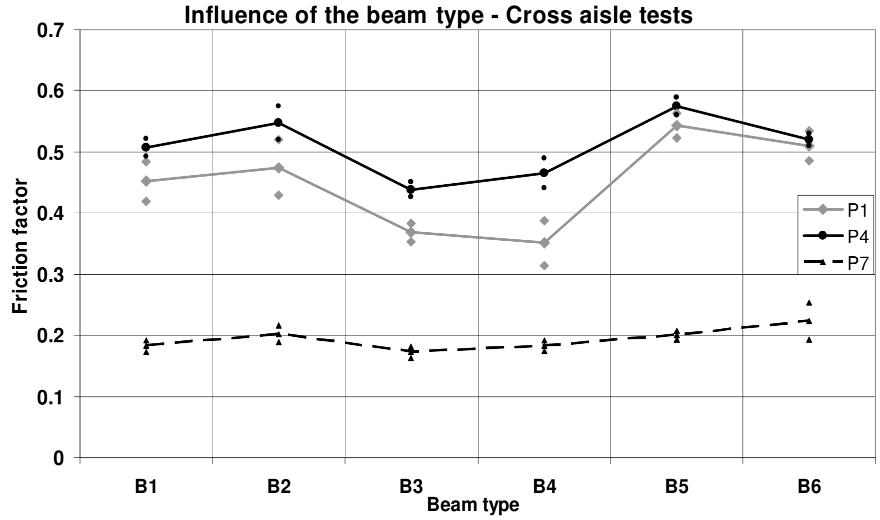


Fig. 6: Friction factor in cross-aisle direction for different beam types and pallets

Table 3: Statistics of test results for Pallet P4 and different types of beam

	μ	σ	*Cov%*	*Max*	*Min*	Δ^+ %	Δ^- %	$\mu+\sigma$	$\mu-\sigma$	$\mu+2\sigma$	$\mu-2\sigma$	α^+	α^-
B1	0.51	0.01	2.9	0.53	0.46	5.2	9.1	0.52	0.49	0.54	0.48	1.80	3.13
B2	0.55	0.03	5.1	0.59	0.47	8.3	13.3	0.58	0.52	0.60	0.49	1.63	2.62
B3	0.44	0.01	2.7	0.46	0.41	5.4	5.5	0.45	0.43	0.46	0.42	2.00	2.05
B4	0.47	0.02	5.2	0.51	0.42	9.2	9.1	0.49	0.44	0.51	0.42	1.77	1.73
B5	0.57	0.01	2.5	0.61	0.54	5.7	5.3	0.59	0.56	0.60	0.55	2.33	2.13
B6	0.52	0.01	2.0	0.54	0.49	3.3	5.0	0.53	0.51	0.54	0.50	1.65	2.45

Table 4: Statistics of test results for Pallet P7 and different types of beam

	μ	σ	*Cov%*	*Max*	*Min*	Δ^+ %	Δ^- %	$\mu+\sigma$	$\mu-\sigma$	$\mu+2\sigma$	$\mu-2\sigma$	α^+	α^-
B1	0.18	0.01	5.2	0.20	0.16	11.7	11.0	0.19	0.17	0.20	0.16	2.24	2.10
B2	0.20	0.01	6.8	0.25	0.18	24.0	12.5	0.22	0.19	0.23	0.17	3.51	1.83
B3	0.17	0.01	5.7	0.19	0.16	10.5	9.3	0.18	0.16	0.19	0.15	1.85	1.63
B4	0.18	0.01	4.6	0.21	0.17	14.8	5.9	0.19	0.17	0.20	0.17	3.25	1.30
B5	0.20	0.01	3.6	0.22	0.19	11.7	4.6	0.21	0.19	0.22	0.19	3.22	1.27
B6	0.22	0.02	8.5	0.26	0.19	20.6	11.2	0.24	0.20	0.25	0.18	2.42	1.32

Similar considerations can be drawn with regards to Figure 6 that shows the influence of the beam type. Test results and their statistical re-analysis, for Pallets P4 and P7, are presented in Table 3 and Table 4. Pallet P4 (American wooden Pallet) shows the highest value of the friction factor, pallet P1 (Wooden Euro Pallet) an intermediate one and pallet P7 (Plastic Euro

Pallet) the lowest one. Friction factor for pallet P7 is quite constant, while for the other two types of pallet the friction factor shows a strong dependence on the beam type. For pallets P1 and P4 the highest friction factor is obtained with beam B5.

The re-analysis of the results in case of pallet P1 and P4 (Wooden Euro pallet and American pallet) and of the groups of beams B1+B2+B5+B6 shows that the response of the groups of beams (B1+B2+B5+B6) is rather homogeneous. A mean value of the static friction factor of 0.52 was obtained, with a c.o.v. of 8.9%. In the case of the beam types B3 and B4, data seem to be less homogeneous than those of the other group of beams. Mean values of the static friction factor respectively 0.40 and 0.41, with a c.o.v. of 13.1% and of 15.8%, were obtained.

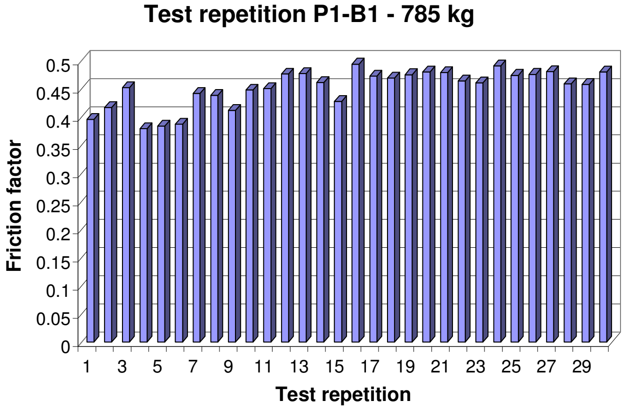


Fig. 7: Repetition of tests carried out with pallet type P1 - beam type B1

Figure 7 shows the repetition of tests for pallet type P1 for beams B1. The observed behaviour for the other types of beams is similar, therefore the reported graph is quite exemplary, also for the other types of pallets. In the first tests, the friction factor shows an increasing trend while, after 5-10 tests, the obtained value is practically constant. This is most probably due to the "wearing" of the surface of the beam. In the first tests, the beam is new, and the friction factor is low. Due to wearing, the surface roughness increases, together with the friction factor as well as the scatter of the results. Beyond a certain level, the phenomenon stabilizes.

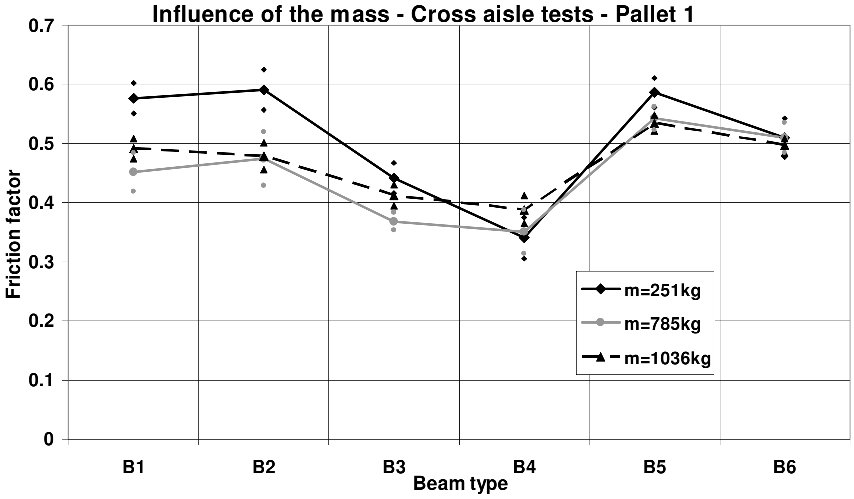


Fig. 8: Friction in cross-aisle direction for different beam types and three values of the mass

4.2 Influence of the applied mass

The influence of the applied mass is measured applying masses of 251 kg, 785 kg and 1036 kg for pallet type P1 and for different types of beam. The mass is fixed on the pallet so that there is no relative displacement.

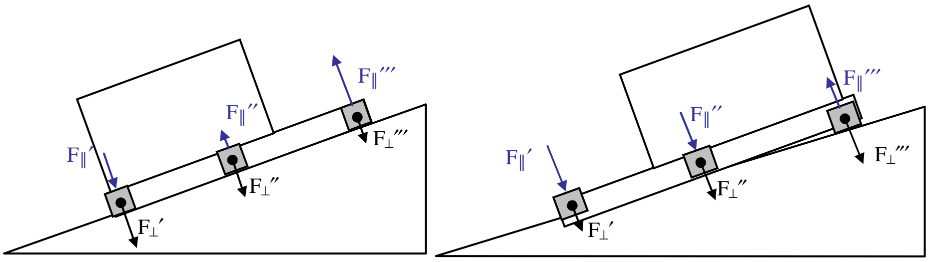
Applied mass strongly influences the friction factor only for beams B1, B2 and B3, while in the other cases it is quite constant. It can be noticed (Figure 8) that the scatter of the data decreases when the applied mass increases. Usually, the highest value of the friction factor is obtained with the mass of 251 kg independently of the beam type, while the lowest one with the intermediate mass. Exceptions are beams B4 and B6.

5 STATIC FRICTION IN DOWN-AISLE DIRECTION

In practice, sliding in this direction is less dangerous than in cross-aisle direction, because the fall of the pallet can occur only if other pallet displacements take place. In any case, with a test set up similar to that adopted for cross aisle experiments, quasi-static sliding tests were carried out analyzing the same parameters as in cross-aisle direction. The obtained results were quite similar: the influence of the pallet type, the beam type and of the value of the applied mass showed a similar behavior to the cross-aisle tests.

5.4 Influence of the mass eccentricity

The influence of the mass eccentricity was investigated only in the down-aisle direction. The position of the mass on the pallet (centered or eccentric downward and upward) determines a different distribution of the weight force on the beam, that can influences the value of the friction factor. The weight of the mass can be divided in two components, $F_\perp$ and $F_\parallel$ due to the inclined plane. $F_\perp$ decreases during the test performed increasing the inclination θ of the plane on the horizontal, $F_\parallel$ increases, being: $F_\perp = F \cos\theta$ and $F_\parallel = F \sin\theta$. The orthogonal component can be considered distributed on the three series of blocks of the pallet with the three components $F_\perp'$, $F_\perp''$ and $F_\perp'''$ (as shown in Figure 9c). The parallel component $F_\parallel$ (applied in the c.o.g. of the mass) is resisted by the "friction", on the beam-to-pallet interface. As a consequence $F_\parallel$ has a lever arm with respect to the sliding plane, where the friction reaction develops. The effect of such an overturning moment is to increase the reaction on the wooden block n°1 with the force $F_\parallel'$, and to decrease the one on the third block with the $F_\parallel''$ component.



a) b)

Fig. 9: Components of the forces in a downward (a) and upward (b) position

When the mass is positioned downward, the orthogonal reaction on the block n°3 is lower than that on blocks n°1 and n°2. Therefore, the effect of the overturning moment is to increase the reaction on block n°1 and reduce that on block n°3. The result is an "uplift" of the block n°3, i.e. a reduction of the contact surface (Figure 9a). If the mass is centered on the pallet this effect is reduced. On the contrary, when the mass is positioned with an "upward" eccentricity, the effect due to the overturning moment somehow compensates the non-uniform distribution of the reactions perpendicular to the sliding surface resulting in a more uniform distribution of the weight of the pallet, "maximizing" the contact surface (Figure 9b). Experimental results confirm the previous considerations. The variations of the friction coefficient due to differences in the eccentricity of the mass are in any case very small. For the combination of Pallet type P4 (Wooden American Pallet) with a beam type B6, the mean values, with quite small *Cov.* are: 0.49 for downward eccentricity, 0.50 for a centred load, and 0.55 for an upward eccentric load.

CONCLUSIONS

Assessment of the static sliding conditions of pallets stored on steel racking systems was carried out in both down and cross-aisle direction, by means of an "inclined plane" device.
Influence of the type of beam was investigated by adopting six different types of beam specimens, manufactured by three different producers, with different types of surface finish. In particular, hot zinc, hot dip and powder coated steel beams were considered.
In both cross and down-aisle direction, the surface finish influenced very much the static friction factor, with differences as large as 20-30% from one type to the other, in the case of wooden pallets. Three different types of pallets were adopted, namely: wooden Euro pallets, wooden American-pallet and plastic Euro pallet. In both cross and down-aisle direction the plastic Euro pallet showed a very low friction factor (of the order of 0.2). The wooden pallets show a very similar friction factor (of the order of 0.5), and are similarly influenced by the beam surface finish. In both cross and down-aisle direction, the mass weight didn't affect much the results. However, its geometry (height of the c.o.g.) and its "placement" on the pallet (centred or eccentric) resulted in small variations of the measured friction factor.

REFERENCES

Coulomb C.A., 1776, Essai sur une application des regles de maximis et minimis à quelques problemes relatifs à l'architecture, Memoires de Mathèmatique et de Physique, Academie Royale des Sciences, Paris, 7, pp.343-382

Haessig D. A. and Friedland B., 1991, On the modelling and simulation of friction. J. Dyn. Syst. Meas. Control Trans ASME, 113(3), pp.354–362.

Morin A.J., 1833, New friction experiments carried out at Metz in 1831-1833, in Proc. Of the French Royal Academy of Sciences, 4, pp. 1-128

Castiglioni C.A., 2003, Dynamic tests on steel pallet racks, Costruz. Metalliche, 3, pp. 35-44

Degee H., Denoel V., Castiglioni C.A., 2008, Seismic Behaviour of Storage racks made of Thin-Walled Steel members, VII EU Conf. on Structural Dynamics, Eurodyn 2008

Castiglioni C.A. et al., 2009, Seismic Behaviour of Steel Storage Racking Systems, Proceedings of XXII CTA, Padova.

Castiglioni C.A., 2008, Seismic Behaviour of Steel Storage Pallet Racking Systems, PhD Thesis, University of Genova.

RFCS, 2008, Storage racks in seismic areas (SEISRACKS), Final Report, RFCS Contract n. RFS-PR-03114

FEMA 460 (2005), Seismic Considerations for Steel Storage Racks Located in Areas Accessible to the Public

KEYWORDS

Racking systems, seismic behaviour, static friction, sliding tests