Earthquake-Induced pallet sliding in industrial racking systems

Carlo A. Castiglioni[a], Alberto Drei[a,*], Alper Kanyilmaz[a], Harris P. Mouzakis[b]

[a] Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Milan, Italy
[b] National Technical University-Laboratory of Earthquake Engineering, Athens, Greece

This paper discusses the sliding behaviour of pallets in industrial racking systems under dynamic actions. For this purpose, a summary of the results of an extensive series of dynamic shake-table tests are presented; complete results of this extensive testing campaign may be found in a recently published book. Dynamic and seismic tests have been performed using three beam types with different surface finish materials, in both the Cross-Aisle (CA) and Down-Aisle (DA) directions. Lower and upper bound accelerations were determined from the uniaxial dynamic tests. Several phenomena related to deformations of the supporting beams (i.e. in- and out-of-plane bending) were found to affect the pallet behaviour, in both the CA and DA directions, with sliding occurring at very low acceleration levels. The same behaviour was observed during uniaxial earthquake tests. For biaxial seismic testing, lower bound acceleration in the CA direction was higher than in dynamic cyclic tests, whereas the opposite was observed in the DA direction.

Keywords:
Racking systems Pallet
racks
Dynamic friction
Shaking table
Beam-pallet interaction
Pallet sliding

1. Introduction

Despite their light self-weight, industrial racks usually carry very heavy unit loads and can raise considerable heights. Such structures are commonly adopted in warehouses, where they are loaded with tons of valuable goods, and frequently they are present in buildings open to the public, as supermarkets and shopping centres [1–7]. They are designed using cold formed steel profiles and hook-in beam-to-upright connections to ease the installation and reconfiguration, to satisfy the merchandising needs of the warehouse retail stores. The typical wooden pallets have approximately one square meter (1200 × 800 mm Europallet size or 48″ x 40″ American Type size) of plan area and usually have unit loads of approximately 8–10 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. In industrial warehouse facilities, racking systems can reach considerable heights of 12–15 m. The longitudinal direction of the racks is nominated as "Down-aisle" (DA), and the transverse di-rection as "Cross-aisle" (CA). In the DA direction, proprietary moment connections made of beam-end connectors provide the lateral stability, while in the CA direction, bracings are used [8–10].

When a strong earthquake hits the warehouse, the pallets may fall down and this endangers the life of customers and employees. Besides, the loss of the goods may cause a significant economic damage, which would be much larger than the cost of the whole rack structure. Moreover, seismic upgrading solutions typically used also for the industrial buildings [11,12] are not suitable for industrial racks further complicating the problem. Sliding of the pallets on the racks and their consequent fall represents an additional 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 coefficient between the pallet and the steel beams of the rack [13–16]. Some researchers studied such phenomenon by means of static tests [17,18]. At present, there are technical limitations concerning the safety and design of storage racks in seismic areas, which challenge the structural behaviour regarding the ductility and pallet sliding conditions. To solve some of these limitations, the EU sponsored an RTD project titled "Storage Racks in Seismic Areas" (acronym SEISRACKS, contract number: RFS-PR-03114) [19], including an experimental research on the static and dynamic friction behaviour of the coupling steel beam-wooden pallet, that consisted in about 1260 static tests and 182 dynamic tests. This paper presents a summary of the results of the large campaign of shake table testing performed to study the pallet behaviour under dynamic conditions, and identify the load unit accelerations that may transfer extra horizontal actions to the rack frame as a function of the input motion characteristics (in terms of acceleration and frequency, and of the pallet-beam interface characteristics).

Dynamic tests have been carried out using beam specimens with different surface finishes. Sinusoidal excitations have been applied to the specimens in both the CA and DA directions, using different exciting frequencies with increasing or constant acceleration values. Some

* Corresponding author.
E-mail addresses: carlo.castiglioni@polimi.it (C.A. Castiglioni), alberto.drei@polimi.it (A. Drei), alper.kanyilmaz@polimi.it (A. Kanyilmaz), harrismou@central.ntua.gr (H.P. Mouzakis).

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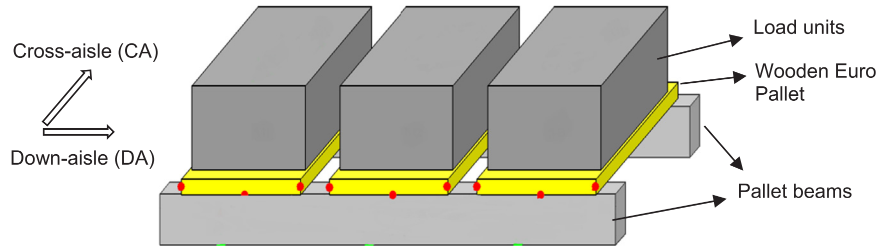


Fig. 1. Test specimen configuration.

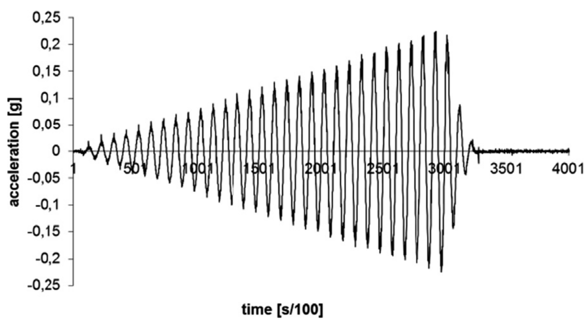


Fig. 2. Shake-table acceleration in 10 tests at 1.0 Hz frequency.

seismic tests were also performed on the same specimen types, to observe a comparison with the results of the sinusoidal tests. The test results have been interpreted by re-analysis of the recorded measurements of the LVDTs and accelerometers installed on the beam and pallet specimens. The static tests, considering the influence of the type of pallet and beam, the stored mass and the mass eccentricity, have been presented in another paper on this journal [20]. The complete and detailed presentation of the experimental activity on pallet-beam friction is extensively reported in a long chapter of the recently published book "C.A. Castiglioni – Seismic Behaviour of Steel Storage Pallet Racking Systems – Springer International Publishing Switzerland, 2016 – ISBN 978-3-319–28465–1" [16]. The authors refer to this book for more details of the experimental activity hereafter presented.

2. Test set-up

The tests have been performed at the Laboratory of Earthquake Engineering (LEE) of the National Technical University of Athens (NTUA), to assess the dynamic "pallet-beam" interaction phenomena under several conditions. General test-layout is shown in Fig. 1. Sliding tests were performed with three different beam types (B1, B2 and B3) and Wooden Euro Pallet 800 × 1200mm (old and dry) both under the CA and DA directions. In order to minimize the bias of the results due to "operating conditions", pallets were positioned at equal spacing on the beams and "re-positioned" in their initial configuration at every test, checking the horizontality of the structure. Masses, 785 kg on every pallet, were fully "fixed" on pallet to avoid rocking and relative movement. Every 10 tests, both the beam-to-upright connection and the base connections of the rack are checked for possible damage (looseness or permanent deformation) and eventually replaced. The beam-to-upright and the base plate connections have been visually checked after each set of ten tests, and replaced if a looseness or permanent deformation were identified.

The types of excitations were the following:

- Sinusoidal with constant frequency, from 1.0 *Hz* to 4.0 *Hz*, and increasing acceleration (increasing displacement amplitude). 97 tests were performed in the CA, 36 tests in the DA direction.
- Sinusoidal with constant acceleration and increasing frequency (displacement amplitude decreases). 27 tests were performed in the DA direction.
- Seismic shaking with three recorded input motions, 22 tests were performed.

The following sections provide the loading protocol and the related instrumentation for these three excitations, and present the outcomes of the sinusoidal and seismic excitation tests in the CA and DA directions and the relevant discussion of results and conclusions.

3. Data analysis

The obtained experimental measurements have been investigated in the following sub-sections that are separated according to the loading direction, excitation type and beam and pallet types. The experimental outcomes have been commented and then discussed in Section 4.

3.1. Sinusoidal excitation tests in the CA Direction

In the CA direction, tests were performed applying a constant frequency sinusoidal excitation to the shaking table (Fig. 2). The applied accelerations have been increased gradually. Type B1 beam was a cold rolled, powder coated, new profile, Type B3 beam was a cold rolled, hot zinc coated, new profile.

Fig. 3 and Fig. 4 show the instruments that are used to monitor the displacements and the accelerations of the system. In particular, the following instruments have been used:

- In X (CA) direction: 6 accelerometers (3 on a beam under each load unit and 1 on each load unit); 12 LVDTs (2 on each pallet and 6 on a beam, 2 below each load unit)
- In Y (DA) direction: 3 accelerometers (one for each load unit);

The onset of the sliding was identified from the displacement outputs, when the pallet and beam displacements started to differ (Fig. 5). This was more evident in the case of Pallet 1 and Pallet 3 (external ones), and not in Pallet 2 (central) because the sliding of the external

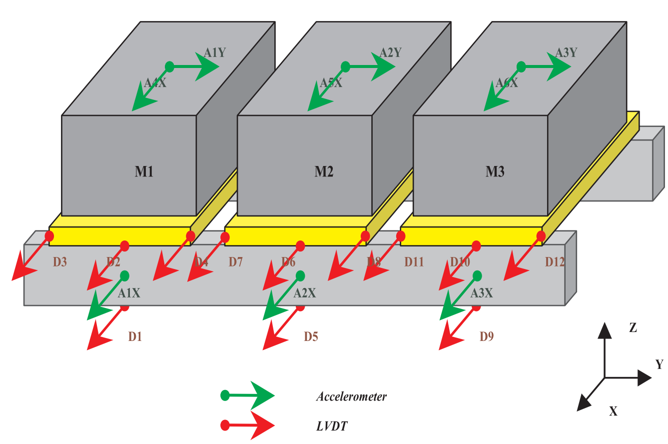
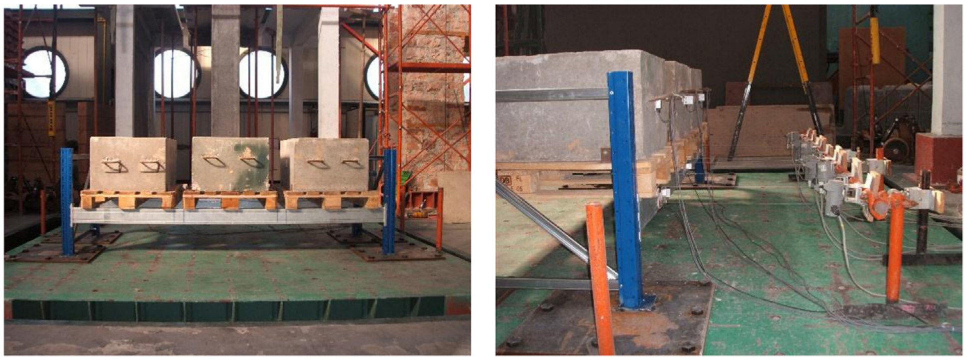


Fig. 3. Instrumentation set up for CA tests.



a. General view b. Instrumentation

Fig. 4. A photo from the test set-up.

ones started earlier and the tests were stopped after a few seconds following the sliding, to avoid too large displacements and the falling of the pallets.

The pallet acceleration values initially follow the acceleration of the beam, then increase up to reach a sort of “limit value of acceleration”. Fig. 6 presents the minimum and the maximum acceleration values of the masses, which were measured at every excitation cycle. Because of the out-of-plane deformability of the beams (in the CA direction), a high acceleration amplification is observed at the specimen (both at the masses and the beams) with respect to the accelerations of the shaking table. The pallet accelerations increase up to a maximum and then remains constant during sliding, while the beam accelerations has a continuously increasing trend.

Fig. 7 shows the images of the beam and the pallets when the tests are finished. A peculiar aspect of the sliding phenomenon highlighted in some tests was a difference of phase among the shaking table, the beam and the masses after the beginning of sliding. At the end of the tests, the sliding of the pallet on the beam could be observed; in some cases, the pallet was nearly losing the support. The “deterioration” of the surface of the beams was evident, as the paint film was scratched and removed by the movement of the wooden pallets.

The outcomes of the tests have been analysed with reference to two parameters:

- Lower bound acceleration: the acceleration of the mass corresponding to the initiation of the pallet sliding;
- Upper bound acceleration: Once the mass reaches this value, it remains constant until the end of pallet sliding. This value can be related to the maximum force acting on the rack during an event: beyond that, pallets slide and their mass can be considered independent of the rack.

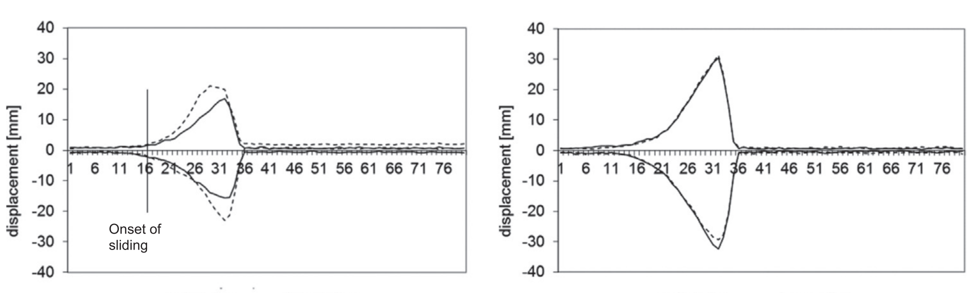
Pallet sliding did not take place in some of the tests; mainly those with the low frequency content. When the maximum horizontal excursion of the shaking table reached ± 100 mm, the test had to be stopped. For low frequency such as 1.0 Hz, such condition took place for shaking table acceleration of nearly 0.2 g, which was lower than the upper bound of the sliding acceleration.

3.1.1. *CA tests – beam type B1*

This sub-section presents the results of the tests carried in the CA direction for beam type B1 (cold rolled, powder coated, new beam). The increment rate of the shaking table acceleration was generally 0.01 (g)/s; for some groups of tests lower values were adopted such as 0.009 (g)/s, 0.008 (g)/s and 0.005 (g)/s. The upper bound values could be reached only in some of the experiments. Table 1 shows the statistical re-analysis of the test data grouped according to frequencies from 2.0 to 4.0 Hz and the same input signal type. In the 10 tests at 3.0 Hz and in the 6 tests at 4.0 Hz frequency, the upper bound acceleration was reached for each pallet. When the frequency of the table acceleration is very low (e.g. 1.0 Hz) sliding occurs only on the external pallets, while no relative displacement occurs between the central pallet and the beam. In the same way, also the upper bound of the sliding acceleration of the masses is reached earlier for the external pallets, and later by the central one, due to the fact that the external pallets reach a higher value of the sliding acceleration earlier than the central one.

Table 2 shows for each pallet, the acceleration values at the onset of sliding (lower bound) and their upper bound values, independently of the frequency of the table acceleration.

Under excitation in the CA direction, the relative displacement between the external pallets and the beam (near to the beam-to-upright connection), is larger than the relative displacement observed in the central position. The experimental observations confirmed that the external pallets are not only subjected to a horizontal acceleration component in the CA direction, but, due to the rotation of the beam near the supports, they are also subjected to a torsional component. For this reason, sliding of the external pallets occurs already under rather low values of accelerations. On the contrary, in the central position the rotation of the beam is smaller, as the possibility of sliding of the pallet. Therefore, the central pallet sliding starts at higher values of the table



a. Pallet 1 b. Pallet 2

Fig. 5. Displacement of pallets and beam: Pallet 1 (external), Pallet 2 (central) - test aa23.

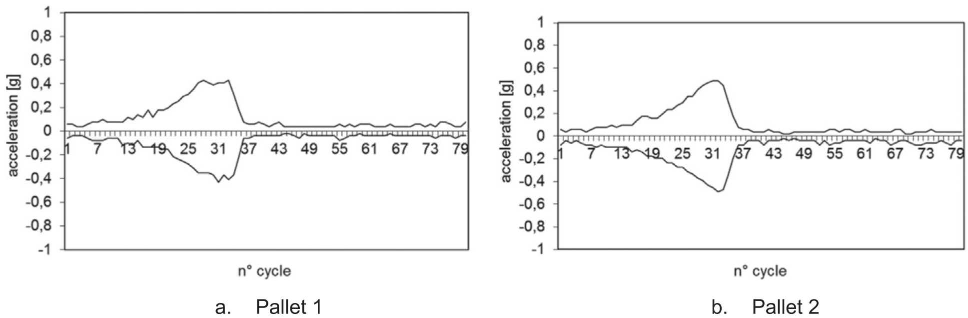


Fig. 6. Maximum and minimum accelerations of Pallet 1 (external), and Pallet 2 (central) - test aa23.

acceleration and the possibility of torsional effects is small. For the low frequencies, such values of acceleration could not have been reached due to the limited excursion of the shaking table.

Different tests provide slightly different lower and the upper bound acceleration values, as the stiffness of the joints to some extent differ one from another, due also to the damage accumulated during testing. From Fig. 8, it can be noticed that the sliding initiation of all pallets and the upper bound accelerations for the external pallets show a linear decreasing trend when the frequency increases. On the other hand, for the central pallet, which starts to slide at higher values of acceleration, upper bound values are more or less constant (Fig. 8.c).

3.1.2. CA tests – beam type B3

This sub-section presents the results of the tests carried in the CA direction for beam type B3 (cold rolled, hot zinc coated, new beam). The increment rate of the shaking table acceleration was generally 0,01 (g)/s. Ten tests were performed at 1.0 Hz frequency applying a lower table acceleration increment of 0008 (g)/s. Maximum table accelera-tion was 0,2 g. Table 3 reports the data obtained. Also in this case, with beams B3, at 1.0 Hz frequency there was no sliding in the central pallet. Table 3 reports the data obtained for all the tests performed at higher frequencies. In the 10 tests at 1.5 Hz, in some cases the upper bound acceleration was reached, with significant values between 0,4 and 0,5 g.

Table 1
Statistics of CA tests – beam type B1.

		Pallet 1		Pallet 2		Pallet 3	
		Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]
1.0 Hz	μ	0,19	0,29			0,19	0,27
10 tests	σ	0,02	0,01			0,01	0,01
0.01 (g)/s	Cov %	8,65	3,47			5,88	5,30
2.0 Hz	μ	0,17	0,24	0,27		0,19	0,27
10 tests	σ	0,02		0,02		0,01	0,01
0.01 (g)/s	Cov %	12,35		7,58		6,32	2,64
2.0 Hz	μ	0,18		0,31		0,19	
4 tests	σ	0,02				0,02	
0.008 (g)/s	Cov %	9,44				9,34	
2.0 Hz	μ	0,18		0,30		0,16	
6 tests	σ	0,02		0,01		0,01	
0.005 (g)/s	Cov %	8,62		4,73		6,21	
3.0 Hz	μ	0,16	0,20	0,25	0,32	0,18	0,23
10 tests	σ	0,01	0,00	0,02	0,02	0,02	0,01
0.01 (g)/s	Cov %	7,10	2,02	6,17	5,47	9,50	4,95
4.0 Hz	μ	0,13	0,17	0,16	0,31	0,12	0,22
6tests	σ	0,01	0,02	0,01	0,01	0,01	0,01
0.009 (g)/s	Cov %	6,06	12,50	4,52	3,91	5,26	4,61

Fig. 7. Images of beam and pallets residual displacements and beam deterioration at the end of the tests.

Table 2
Lower and upper bound acceleration values for each pallet – beam type B1.

CA – all table frequencies						
	Pallet 1		Pallet 2		Pallet 3	
	Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]
μ	0,17	0,21	0,24	0,31	0,18	0,24
σ	0,02	0,04	0,05	0,02	0,03	0,02
Cov %	13,19	21,36	20,39	4,93	15,29	10,19

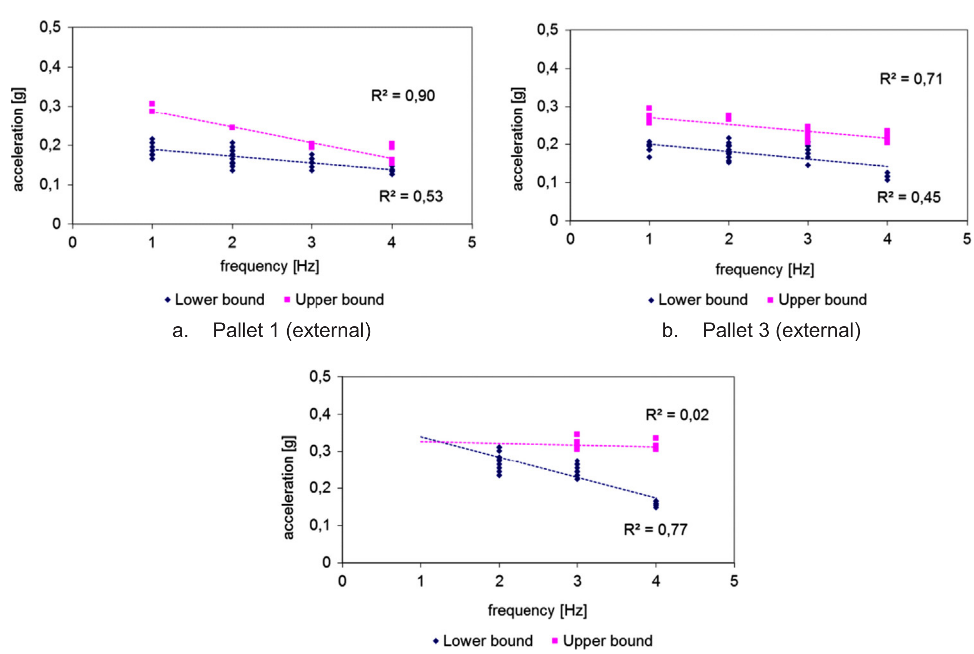
Table 3
Data of P2-B3 test.

		Pallet 1		Pallet 2		Pallet 3	
		Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper Bound [g]
1.5 Hz	μ	0,14	0,44	0,35	0,43	0,14	0,41
10 tests	σ	0,02	0,04	0,03	0,03	0,02	0,03
	Cov %	11,51	10,05	7,35	7,29	13,33	6,20
2.0 Hz	μ	0,16	0,40	0,39	0,50	0,14	0,40
5 tests	σ	0,01	0,01	0,06	0,02	0,02	0,01
1st group	Cov %	3,14	2,54	15,76	3,07	14,08	2,58
2.0 Hz	μ	0,15	0,44	0,41	0,50	0,16	0,40
5 tests	σ	0,00	0,03	0,04	0,01	0,01	
2nd group	Cov %	2,72	6,98	10,37	2,86	5,81	
2.0 Hz	μ	0,16	0,42	0,40	0,50	0,15	0,40
whole batch	σ	0,01	0,03	0,05	0,01	0,02	0,01
	Cov %	5,23	6,60	12,79	2,66	10,81	2,06
2.5 Hz	μ	0,16	0,29	0,31	0,39	0,13	0,25
11 tests	σ	0,03	0,01	0,02	0,02	0,02	0,01
	Cov %	17,09	3,14	5,83	5,48	16,15	5,35
3.0 Hz	μ	0,13	0,21	0,23	0,40	0,15	0,22
5 tests	σ	0,01	0,01	0,01	0,02	0,02	0,01
0.007 g/s	Cov %	10,08	6,25	4,95	4,57	14,67	3,77
3.0 Hz	μ	0,15	0,20	0,25	0,42	0,16	0,21
5 tests	σ	0,02		0,03	0,04	0,02	0,01
0.01 g/s	Cov %	9,87		13,25	10,58	11,61	3,85
3.0 Hz	μ	0,14	0,21	0,24	0,41	0,15	0,21
all 10 tests	σ	0,02	0,01	0,03	0,03	0,02	0,01
	Cov %	12,86	4,90	11,49	8,40	12,50	3,81

For 2.0 Hz frequency, there are two groups of tests, with different maximum durations, respectively 20 s and 16 s. Tests were stopped when the sliding of at least one pallet could be visually detected. This operative decision was taken to minimize damage to the beams and to minimize the displacement of the pallets, reducing the time for their "repositioning" between one test and another. The batch of hot zinc coated beams was limited, because some beams had been damaged, probably during shipping. Therefore, it was impossible to replace the beams after 10 tests, according to the adopted standard procedure, and the same beam was used for 30 tests. First 5 tests were run for each frequency (2.0, 2.5 and 3.0 Hz respectively) and then other 5 tests were repeated for the same frequencies (starting again from 2.0 Hz, then 2.5 and 3.0 Hz). Scatter in some of the results is probably due to the deterioration either of the beam surface or of the external end-plate connections (or a combination of these two effects).

Table 4 shows for each pallet, the acceleration values at the onset of sliding (lower bound) and their upper bound values, independently of the frequency of the table acceleration. For the same reasons discussed with reference to tests carried out with beam type B1, also in this case sliding starts first for the external pallets. Sliding of the central mass occurs under much higher accelerations. In some cases, sliding of the central mass could not be developed because the tests were stopped before the attainment of the limit conditions.

The acceleration of sliding initiation (lower bound) has almost a constant value independent of the frequency of the excitation for the two external pallets, while for the central one it shows a decreasing trend when the frequency increases (Fig. 9.a). At low frequency, e.g. 1.0 Hz, only the two external pallets slide on the beam, while the central one does not show any relative displacement. Data show that the two external pallets start sliding more or less for the same acceleration, for every considered frequency, with the exception of the case of 2.5 Hz, in which the sliding acceleration of pallet 3 (0,13 g) is lower than that of pallet 1 (0,16 g), and the case of 3.0 Hz, in which pallet 1 begins to slide at 0,14 g while pallet 3 at 0,15 g. The upper bound value of the acceleration of the two external pallets shows a strongly decreasing trend when increasing the frequency, although values at 1.0 Hz are in countertendency (Fig. 9.b). The upper bound of the sliding



a. Pallet 1 (external) b. Pallet 3 (external)

c. Pallet 2 (central)

Fig. 8. Sliding initiation and the upper bound acceleration values - B1 tests in the CA direction.

Table 4
Statistics of CA tests – beam type B3.

CA – all table frequencies						
	Pallet 1		Pallet 2		Pallet 3	
	Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]	Lower bound [g]	Upper bound [g]
μ	0,15	0,31	0,32	0,43	0,14	0,28
σ	0,02	0,09	0,07	0,05	0,02	0,08
Cov %	13,79	28,52	21,20	11,00	14,39	28,00

acceleration is similar for the three pallets in the case of 1.5 Hz frequency. The overall similarity of the behaviour of Pallet 1 and Pallet 3 can be observed. Sliding starts with an acceleration of about 0,15 g, for both pallets, and this value remains almost constant independent from the frequency. Considering the data of both the external pallets, the mean value is 0,14 g, the standard deviation is 0.02 g and the c.o.v. is 14%.

3.1.3. CA tests – Comparison of results

In this sub-section, CA test results obtained with different beam types (B1 and B3) are compared. Table 5 summarizes the global test results.

In the case of beam B1 (powder coated), the minimum measured acceleration value causing the sliding of at least one of the pallets decreases with increasing excitation frequency, ranging from approximately 0.19 g for a frequency of 1.0 Hz, to 0.12 g for a frequency of 4.0 Hz. Although the beam specimens are frequently renewed between tests and an average value of accelerations have been obtained from several tests, this decrease may have been also caused by the wearing of the sliding surface. On the contrary, in the case of beam B3 (hot zinc coated) the minimum measured value of the acceleration causing sliding of at least one of the pallets is approximately between 0.13 and 0.15 g, and this value is practically independent of the frequency. A similar observation has been also made for B2-type beam (shown in the next sub-sections). The mean values of the accelerations causing the pallet sliding have been compared in Fig. 10, where each graph shows the mean value of the test results obtained with a same frequency of excitation for a single pallet and for different beam types.

The pallet sliding acceleration values that are obtained at the same frequency are shown in Fig. 11. These are obtained as average values of the external pallets 1 and 3, having similar behaviour with both beam types. Up to 3.0 Hz, the data is not significantly influenced by the excitation frequency. Central pallet sliding starts at smaller acceleration values with respect to the external pallets. Under acceleration values lower than 0.11 g, external pallet sliding is not observed. In the whole batch of tests, only one data less of this value was measured: 0.09 g in pallet 3 for the P2-B3 test aa45, at frequency 2.5 Hz.

The mean upper bound sliding acceleration values of the pallets obtained with different excitation frequencies and beam types are shown in Fig. 12. It is seen that the upper bound sliding acceleration is larger in the case of the central pallet. Upper bound accelerations decrease slightly with increasing frequency. The lower bound sliding acceleration of beam type B3 is lower with respect to the beam type B1, while it is the contrary in the case of the upper bound sliding accelerations.

3.2. Sinusoidal excitation tests in the DA Direction – B2 type beam

Tests were performed on beam type B2 with two types of excitation in the DA direction, as shown in Fig. 13: a sinusoidal excitation with constant frequency and increasing acceleration, and a sinusoidal excitation with constant acceleration and increasing frequency.

The test set up, shown in Fig. 14 and Fig. 15 is similar to that adopted for the previous series of tests in the CA direction, but with a different positioning of the instrumentation, composed of:

- In Y (DA) direction; 5 accelerometers; 1 for each load unit and beam. 8 LVDTs; 2 on each pallet and 1 on each beam
- In X (CA) direction: 4 LVDTs, 1 on each external pallet and 2 on the central one;

Since the excitation is applied in the DA direction, no transversal (CA) deformation component was expected at the beams. Fig. 16 shows an example of registered sliding of an external pallet in a test.

The comparison was made for a large data set including constant frequency and acceleration tests. The results of the constant frequency tests for lower and upper bound values are summarized respectively in Table 6 and Table 7. The results of the constant acceleration tests are shown in Table 8. Considering both sets of data obtained in the tests performed with constant frequency and those with constant acceleration, the results look quite compatible. It can be observed that no sliding occurs for accelerations lower than 0.3 *g*. Only one data less of this value was measured: 0,29 g in pallet 3 for CA test aa123, at frequency 1.0 *Hz*. In constant acceleration tests, useful data could be obtained only for the lower bound accelerations, since the tests were terminated before reaching resonance.

The mean acceleration values that cause sliding of the central pallet are presented in Fig. 17.a. When the frequencies are larger than 1.0 Hz, the response is almost independent of the frequency. Since during the tests with 1.0 Hz frequency, the maximum excursion of the shaking table was reached before pallet sliding initiation, these tests are biased, and their reliability is poor. The mean sliding acceleration values for the external pallets 1 and 3 with beam type B2 are shown in Fig. 17.b. Considering the global results, apart from those with frequency 1.0 Hz, 0.4 g can be assumed as a reliable limit value of acceleration for the possible sliding of pallets. The lower value registered is 0,34 g, two others are less than 0,36 g, and a few only less than 0,40 g.

The upper bound sliding acceleration values obtained with different excitation frequencies is slightly higher for the central pallet with respect to the external ones; they increase slightly with increasing the frequency, mainly for the external pallets. The highest mean upper

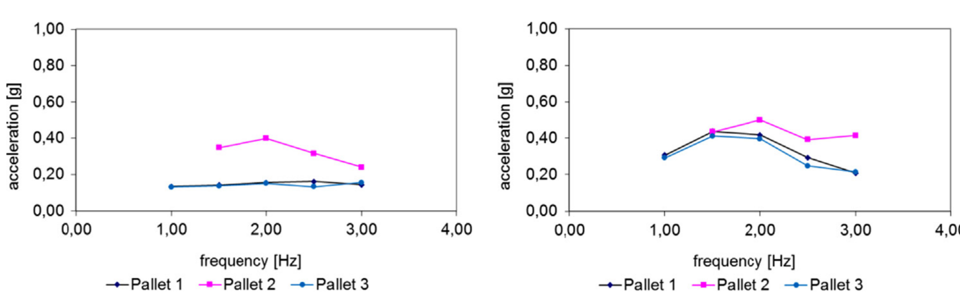


Fig. 9. Lower and upper bounds of sliding acceleration in the CA tests – beam type B3.

Table 5
CA tests: upper and lower bound of sliding acceleration [g] (mean values).

Beam type	Pallet position	Upper/ Lower	Frequency [Hz]					
			1.00	1.50	2.00	2.50	3.00	4.00
B1	External	Lower	0.19 ± 0.01	-	0.18 ± 0.02	-	0.17 ± 0.02	0.12 ± 0.02
		Upper	0.28 ± 0.02	-	0.26 ± 0.02	-	0.21 ± 0.02	0.20 ± 0.03
	Central	Lower	-	-	0.28 ± 0.02	-	0.25 ± 0.02	0.16 ± 0.01
		Upper	-	-	-	-	0.32 ± 0.02	0.31 ± 0.01
B3	External	Lower	0.13 ± 0.01	0.14 ± 0.02	0.15 ± 0.01	0.15 ± 0.03	0.15 ± 0.02	-
		Upper	0.30 ± 0.03	0.43 ± 0.04	0.41 ± 0.02	0.27 ± 0.03	0.21 ± 0.01	-
	Central	Lower	-	0.35 ± 0.03	0.40 ± 0.05	0.32 ± 0.02	0.24 ± 0.03	-
		Upper	-	0.43 ± 0.03	0.50 ± 0.01	0.39 ± 0.02	0.41 ± 0.03	-

bound sliding acceleration measured in the DA direction respectively is 0.55 g and 0.60 g for the external and central pallets. These values are higher than those obtained during the CA direction tests.

Under the pallets' weight, the beams also underwent a vertical deformation. For the external pallets, the maximum rotation was about 10 *mrad* at the end of the tests. Since the three pallets were symmetrically placed on the beams, the rotation was larger at the supports with respect to the beam centre. Such a deformed beam permitted the two external pallets to slide "downhill" or "uphill", depending on the applied acceleration direction. On the contrary, independent from the direction, the central pallet slides only "uphill". For this reason, the external pallets are expected to slide earlier with respect to the central pallet due to gravity.

3.3. Seismic tests

Seismic tests were performed in the DA direction with beam type B2 and in the CA direction with beam type B1. The set-up is the same one used in the tests with sinusoidal excitation. Beam types B1 and B2 have been tested with wooden Euro pallets. In some cases, a biaxial excitation was adopted with acceleration components in both the CA and DA directions. Three types of seismic signals were applied, which were the appropriately scaled samples of real earthquakes occurred in Greece:

- EDESSA signal (Fig. 18.a): registered in Edessa during the Griva earthquake of December 21st, 1990. The magnitude is 5.9 and was recorded on a soft soil at 31 km from the epicentre. The Fourier analysis highlights the presence in the input signal of a predominant frequency at 1.53 *Hz*.
- KALAMATA signal (Fig. 18.b): registered on September 13th, 1986 at 9 km from the epicentre. Its magnitude is 6.2.
- ARGOSTOLI signal (Fig. 18.c): it's a typical near field earthquake, registered during the Cephalonia earthquake of March 24th, 1983 at 10 km from the epicentre. Its magnitude is 5.5 and it's characterized by an acceleration impulse with a time length of about half second.

The earthquake accelerograms were scaled to apply peak ground accelerations (PGA) of increasing values until the initiation of the pallet sliding.

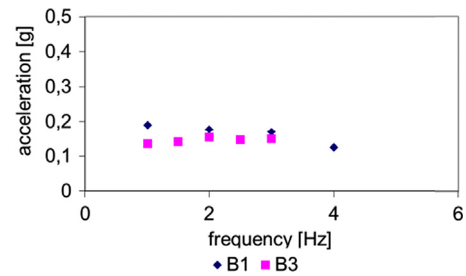


Fig. 11. Sliding of the external pallets in the CA tests (Lower bound - mean values).

3.3.1. Seismic test in the CA direction – Beam type B1

When a relative displacement between the pallet and the beam takes place, the pallet sliding is detected. This corresponds to the sliding acceleration in the seismic test. Observing the general behaviour in the EDESSA and KALAMATA seismic tests (Fig. 19), when sliding occurs there is a final permanent pallet displacement and the pallet can lose support and fall from the beams, while in ARGOSTOLI tests there was no residual final displacement. Some data of the CA seismic tests are summarized in Table 9. The reported acceleration of the pallets refers to the acceleration of sliding initiation, if sliding occurs, or to the maximum acceleration reached during the test if no sliding could be detected.

Fig. 20 shows the lower bound of the sliding acceleration for all tests, considering respectively the data for the two external pallets and the data of the central pallet. These results are comparable with the sliding domain obtained by means of sinusoidal tests in the CA direc-tion. It can be noticed that, sliding occurred first for ARGOSTOLI signal at around 0.15 *g*. For the other tests, the acceleration of sliding initia-tion was higher. For the same reasons described above regarding the sinusoidal CA tests, also in this case, the central pallet starts sliding with accelerations higher than the two external ones. If sliding occurs on the central pallet, its final displacement can be as large as 20 mm.

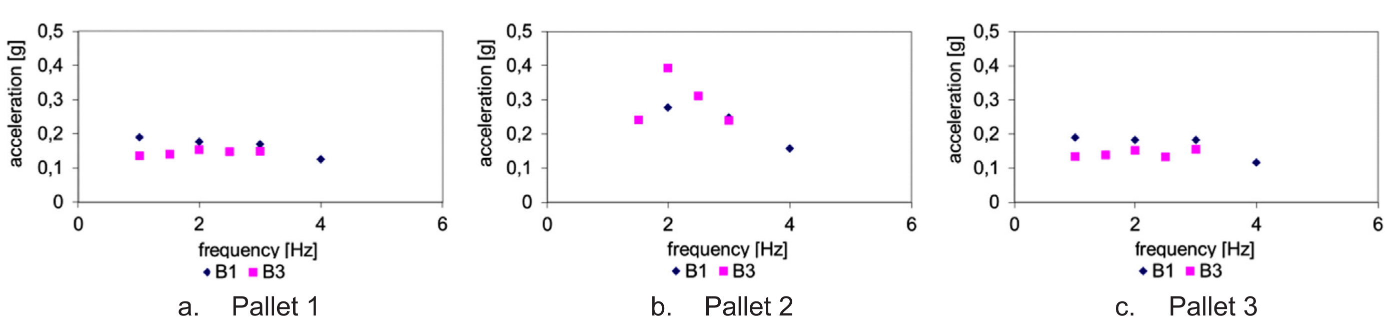


Fig. 10. Response of the CA tests for pallet 1–2–3 (Lower bound - mean values).

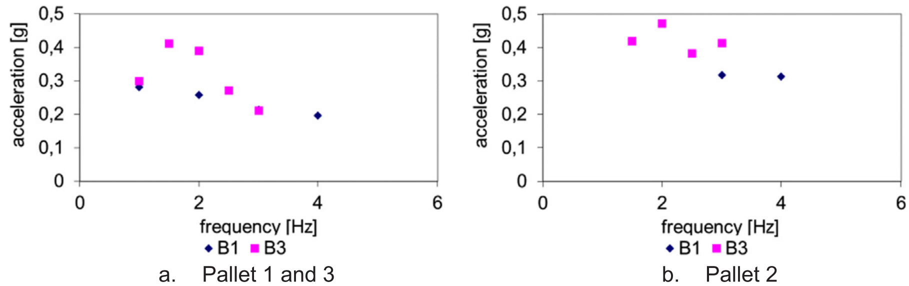


Fig. 12. Upper bound acceleration vs. frequency in the CA tests (mean values).

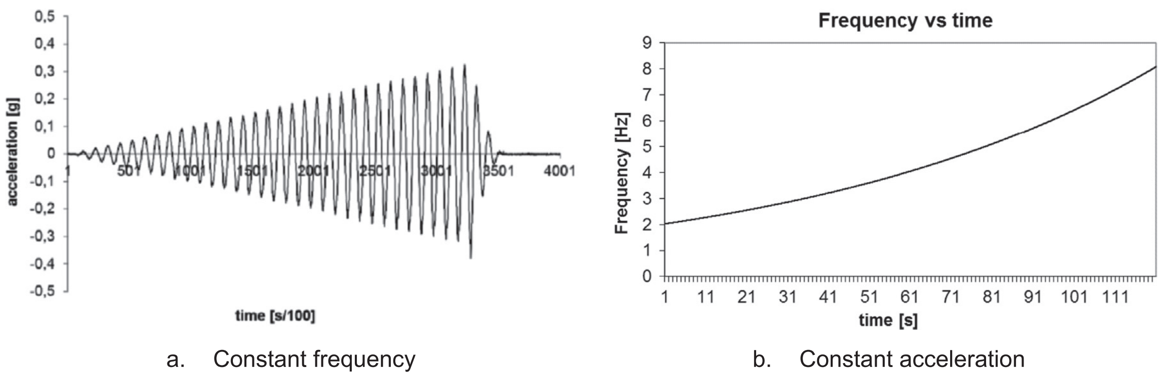


Fig. 13. Sinusoidal excitation types of tests in the DA direction.

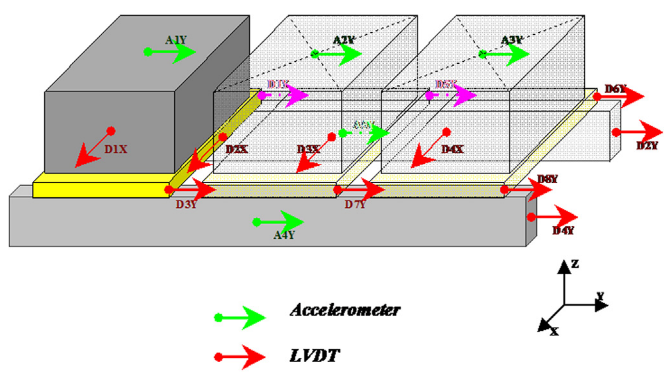


Fig. 14. Instrumentation set up for DA tests.

3.3.2. *Seismic test in the DA direction -Beam type B2*

Seismic tests in the DA direction were performed with beams type B2, with the test set-up used also for sinusoidal excitation. Two tests were performed with the EDESSA and ARGOSTOLI acceleration time histories. Table 10 shows the results in terms of sliding acceleration of the pallets. Pallet sliding starts for pallet acceleration higher than 0.4 *g*.

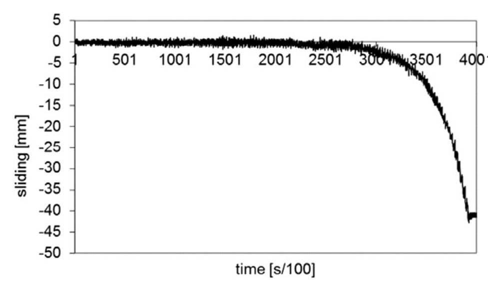


Fig. 16. Sliding of pallet 3 in test n° aa144.

In the DA tests performed with sinusoidal excitation, a similar value was achieved.

During both tests, the three pallets start sliding nearly at the same time. In the case of ARGOSTOLI earthquake excitation, the final displacement of the pallets is larger with respect to the EDESSA earthquake excitation. Pallet sliding takes place first for ARGOSTOLI signal at around 0.45 *g*. Pallet sliding acceleration is higher in the case of EDESSA seismic excitation.

Fig. 15. Experimental set-up and instrumentation for the DA tests.

Table 6
DA tests: Mean acceleration values of pallet sliding initiation [g].

Test type	Pallet position	Frequency [Hz]					
		1.00	1.50	2.00	2.50	3.00	4.00
DA Beam type B2	External	0.33 ± 0.02	–	0.44 ± 0.07	–	0.44 ± 0.06	0.48 ± 0.04
	Central	–	–	0.50 ± 0.07	–	0.49 ± 0.04	0.52 ± 0.00

3.3.3. Biaxial seismic test

Biaxial seismic tests were performed with EDESSA and ARGOSTOLI time history excitations. Table 11 shows the CA (a_{CA}) and DA (a_{DA}) components of the three pallets' sliding acceleration. In all the cases with beam type B1, the lower bound acceleration that triggers the sliding in the CA direction was higher with respect to the one obtained in the sinusoidal tests. The pallet sliding acceleration values of the three pallets were obtained by vector composition of a_{CA} and $a_{DA,}$ and reported in Fig. 21. Since only uniaxial sinusoidal tests were performed, these values obtained from biaxial tests cannot be directly compared with the sinusoidal tests. Therefore, a vector composition was derived with the two lower and upper bound sliding accelerations respectively in the CA and DA directions from sinusoidal tests, which are reported with dotted lines in Fig. 21.

Table 8
Constant acceleration with increasing frequency (first 5 tests did not provide significant values).

	PALLET 1		PALLET 2		PALLET 3	
Test	*f* [Hz]	Lower bound [g]	*f* [Hz]	Lower bound [g]	*f* [Hz]	Lower bound [g]
6	6,81	0,51			6,96	0,48
7	5,66	0,45			6,65	0,46
8	5,4	0,41	7,09	0,55	6,81	0,49
9	5,66	0,46	6,96	0,54	6,42	0,43
10	5,66	0,42				
11	5,04	0,46				
12	5,16	0,48	6,20	0,54	5,92	0,59
13	5,04	0,50	6,35	0,56	5,92	0,59
14	4,98	0,48	6,28	0,56	5,86	0,51
15						
16	2,67	0,48	5,79	0,59	4,49	0,40
17	2,59	0,51				
18	2,61	0,48			3,78	0,42
19	2,61	0,48				
20	2,83	0,43	3,17	0,48	3,17	0,38
21	2,67	0,48			3,65	0,47
22	2,52	0,51			3,56	0,46
23	2,67	0,48	4,65	0,51	3,56	0,45
24	2,61	0,48			4,09	0,43
25	2,45	0,51	2,56	0,54	3,03	0,51
26	2,24	0,56	2,24	0,51	3,10	0,51
27	2,89	0,51	2,30	0,51	3,10	0,51

4. Discussion of results

Shake table tests were performed to study the initiation of sliding of pallets on racking systems and to describe the deformation mechanisms of beams that affect pallet sliding. In the tests, three beam types with different surface finish materials have been used (B1: power-coated, B2: hot-dip coated, B3: hot-zinc coated). Sinusoidal and seismic loading conditions have been applied in both the CA and DA directions, with different exciting frequencies with constant or increasing acceleration values. Three wooden Euro pallets were positioned on the beams, with concrete blocks rigidly fixed on top.

Lower and upper bound of the accelerations have been defined. The lower bound is the value beyond which pallets start sliding on the beams, while the upper bound was the maximum acceleration obtained during the tests. After exceeding the lower bound acceleration, the mass acceleration slightly increased with increasing input acceleration until reaching an upper bound value. When the upper bound value is reached, increasing input accelerations did not affect the accelerations of the mass that is free to slide on the beams. "Stiction" [21] between the pallet and the beam is not resumed until a reduction of the accel-eration occurs. In both the CA and DA directions, external pallets slide systematically earlier than the central one. In other words, lower acceleration values would be needed to initiate the sliding of the external pallets. This can be explained by the fact that the flexural stiffness of the beams in the horizontal plane as well as their torsional stiffness significantly influenced the results. In particular, such stiffnesses were affected by the out-of-plane and torsional behaviour of the beam-to-upright connections, whose stiffness rapidly deteriorates under cyclic loads.

On the test specimens with hot dip coated steel beams, lower bound sliding acceleration as low as 0.1 g was measured. Depending on the beam surface finish type and the pallet's position on the beam, upper bound acceleration values between 0.3 g and 0.5 g were registered. The pallet sliding acceleration values were generally higher in the case of DA direction under the same conditions. Seismic tests were performed under three different input motions previously recorded during recent strong earthquakes in Greece. The acceleration values measured at the beam level positioned at approximately 0.3 m from the table, of course was not affected by the amplification factor that might influence the response in a real structure (for instance, pallets located at the top of a real storage rack would experience a stronger signal, thus closer to a frequency content similar to the ones discussed in this paper but with the difference that the signal would normally not be stationary). Measured sliding accelerations range from 0.15 g to 0.35 g in the CA direction and from 0.45 g to 0.60 g in the DA direction. Although the relevancy of the seismic tests for practice is limited, their results were still compatible with the tests carried out with sinusoidal tests. On the other hand, the results of the sinusoidal excitation tests may be also valid in the seismic situations where a non-stationary signal with one main frequency is governing, as normally observed at a given level of a structure in relation with the concept of floor spectrum. Lower and upper bounds of acceleration that were derived from the dynamic tests

Table 7
DA tests: Upper bound acceleration values of pallet sliding initiation [g].

Test type	Pallet position	Frequency [Hz]					
		1.00	1.50	2.00	2.50	3.00	4.00
DA Beam type B2	External	0.35 ± 0.02	–	0.48 ± 0.07	–	0.52 ± 0.05	0.53 ± 0.05
	Central	–	–	0.56 ± 0.07	–	–	–

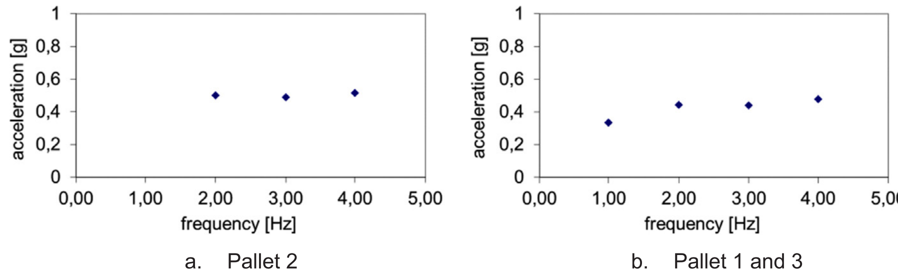


Fig. 17. Lower bound of sliding acceleration in the DA tests (mean values) – B2 type beam.

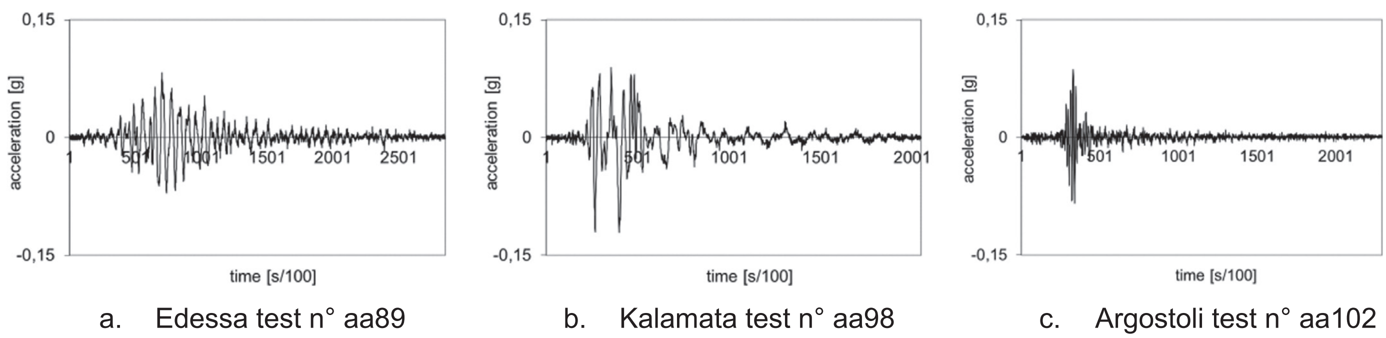


Fig. 18. Acceleration time-history data of the shaking table.

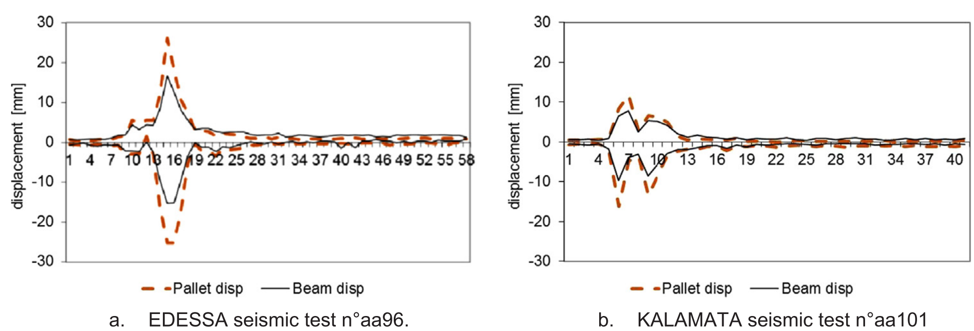


Fig. 19. Displacement of beam and pallet 1.

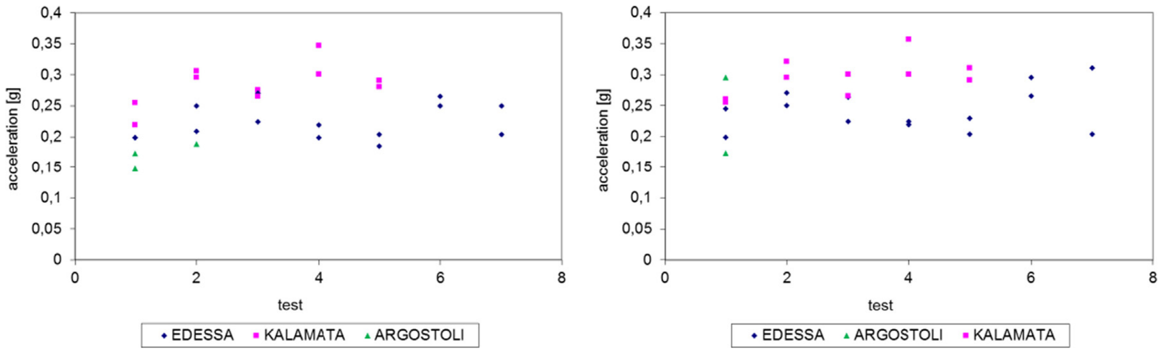
Table 9
Sliding acceleration for CA seismic tests.

Test		PALLET 1		PALLET 2		PALLET 3	
		a [g]	SLIDING	a [g]	SLIDING	a [g]	SLIDING
EDESSA	aa89	0.16	NO	0.15	NO	0.11	NO
	aa90	0.16	NO	0.20	NO	0.15	NO
	aa91	0.17	NO	0.20	NO	0.18	NO
	aa92	0.21	NO	0.25	NO	0.19	NO
	aa93	0.20	YES	0.24	YES	0.20	YES
	aa94	0.25	YES	0.27	YES	0.21	YES
	aa95	0.22	YES	0.26	YES	0.27	YES
	aa96 start	0.22	YES	0.22	YES	0.20	YES
	aa96 end	0.20	YES	0.23	YES	0.19	YES
	aa97 start	0.27	YES	0.30	YES	0.25	YES
	aa97 end	0.20	YES	0.31	YES	0.25	YES
KALAMATA	aa98	0.17	NO	0.20	NO	0.19	NO
	aa99	0.22	YES	0.26	YES	0.26	YES
	aa100/1°	0.31	YES	0.32	YES	0.30	YES
	aa100/2°	0.28	YES	0.30	YES	0.27	YES
	aa101/1°	0.35	YES	0.36	YES	0.30	YES
	aa101/2°	0.28	YES	0.31	YES	0.29	YES
ARGOSTOLI	aa102	0.07	NO	0.13	NO	0.10	NO
	aa103	0.14	NO	0.20	NO	0.11	NO
	aa104	0.15	YES	0.25	NO	0.14	NO
	aa105	0.19	YES	0.30	YES	0.17	YES

cannot be used directly during the design of pallet racking systems. Further numerical and experimental investigations are needed to elaborate more on the beam-pallet interaction, which significantly affects the sliding behaviour.

The dynamic tests performed at local level (beams were supported on the ground) showed that even small values of ground accelerations with wooden pallets on painted or zinc coated steel beams can cause sliding of the pallets. In the case of a whole rack structure, similar configurations are more in danger since the seismic accelerations would be amplified at the higher levels. If the falling of the pallet can be prevented without implying extra impact forces on the rack, this phenomenon can be considered as a resource for the overall global energy dissipation under seismic actions. This would result in a further reduction of the horizontal seismic forces that can be considered in design. Indeed, the results obtained in this research represented a database for the reduction parameter "E_{D1}" introduced in the new standard EN16681 [22]. E_{D1} takes into account the effects of the sliding of the unit loads on supports when the inertial forces exceed the resistance provided by the friction and it is affected by the following parameters:

i. intensity of the seismic action
ii. number of load levels, total mass and flexibility of the racking structure, expressed by the period of vibration (dominant period in the direction considered)
iii. maximum horizontal force that can be transmitted by the pallet to



a. Pallet 1-3 b. Pallet 2

Fig. 20. Sliding acceleration of the external pallets in the CA seismic tests - beam type B1.

Table 10
Sliding acceleration for DA seismic tests.

Seismic motion	Pallet 1		Pallet 2		Pallet 3	
	a [g]	sliding	a [g]	sliding	a [g]	sliding
EDESSA	0.51	yes	0.52	yes	0.53	yes
ARGOSTOLI	0.61	yes	0.45	yes	0.59	yes

the pallet beams, expressed in terms of friction coefficient

The formula reported in the EN16681 [22] for E_{D1} is E_{D1}

$$= \max[0.4; \mu_S/S_e(T_1) + 0.2] \leq 1.0 \quad (1)$$

where

μ_S is the friction coefficient at the interface between unit load and racking structure
T_1 is the fundamental period of vibration of the racking structure in the considered direction (the period with highest modal participating mass in the considered direction)
$S_e(T_1)$ is the ordinate of the elastic spectrum calculated using 3% viscous damping

When pallets are fully restrained on the pallet beams, E_{D1} is assumed equal 1.0 because sliding is assumed not to occur. The friction coefficient to be considered for E_{D1} is the average value obtained by tests or specified by the norms, because it affects the global response of the rack. On the other hand, if the falling of the pallet cannot be prevented, this results in a new limit state that may cause local or global collapse of the rack and injury to the people around the racking system. However, setting a general criterion for the falling limit state is not straight-forward since the prediction of the exact sliding displacement under seismic actions strongly depends on the random nature of the earthquakes.

5. Conclusions

The static and the dynamic friction phenomena were studied for the pallets stored on steel racking systems within the EU-RFCS SEISRACKS research project [19]. Static tests results have been presented in another paper [20]. This paper discussed the results of the shaking table tests that were performed on a simplified set-up, which consisted of two uprights that are connected by horizontal beam at a height of 0.30 m. The tests were performed with three types of beam specimens, using different coating materials. Sinusoidal excitations have been applied to the specimens in both the CA and DA directions, using different constant exciting frequencies varying from 1.0 Hz to 4.0 Hz with increasing or constant acceleration values. Some seismic tests have been performed as well. Test results have been interpreted thanks to the LVDTs and accelerometers installed on the beam and pallet specimens. From the discussions of this paper, the following conclusions can be drawn:

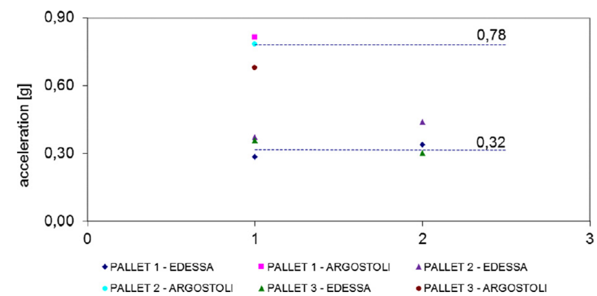


Fig. 21. Sliding initiation acceleration in biaxial seismic tests – Beam type B2.

- CA direction: Sliding is affected by out-of-plane deformation of the beams due to horizontal pallet loads during dynamic excitation. This deformation occurs at a higher angle for the two external pallets and much lower angle for the central one. Therefore, since pallets are rigid, the relative deformation of the beams results in rotation of the (external) pallets. This torsion results in earlier initiation of sliding. The results of high-frequency tests also confirm this, since pallets remained in contact with the beams, even for high acceleration.
- DA direction: In-plane bending of beams due to dead loads introduces an initial angle, which is more pronounced in the case of the external pallets, resulting in earlier sliding initiation for the external pallets than the central one.

Table 11
Sliding acceleration for biaxial seismic tests - beam type B2.

Seismic motion	Test	Pallet 1			Pallet 2			Pallet 3		
		a_{CA} [g]	a_{DA} [g]	sliding	a_{CA} [g]	a_{DA} [g]	sliding	a_{CA} [g]	a_{DA} [g]	sliding
Edessa	aa146	0,19	0,21	yes	0,24	0,28	no	0,24	0,27	no
	aa147	0,21	0,27	yes	0,27	0,34	yes	0,19	0,23	yes
Argostoli	aa149	0,63	0,52	yes	0,60	0,50	yes	0,52	0,43	yes

- The derived lower and upper acceleration bounds determine the initiation of sliding and the maximum developed inertia force, respectively.
- Seismic tests highlight that the interaction phenomena mentioned affect sliding significantly and in the same manner as during dynamic testing.
- For biaxial seismic testing, lower bound acceleration in the CA direction was higher than in dynamic tests, whereas the opposite was observed in the DA direction.
- Lower and upper bounds of acceleration that were derived from the dynamic tests cannot be used for the design of pallet systems. Extensive numerical analyses or experiments have to be carried out to determine the pallet-beam interaction.

Acknowledgements

This article presents the results of the tests performed within SEISRACKS project (Storage Racks in Seismic Areas). The experimental activity was organized by the members of the National Technical University of Athens (Prof. Panayotis Carydis and Prof. Harris Mouzakis) in the Laboratory of Earthquake Engineering.

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