IL PROGETTO EU-RFCS “SEISRACKS2”:
“SEISMIC BEHAVIOUR OF STEEL STORAGE PALLET RACKING SYSTEMS” - PARTE 2: ATTIVITA’ SPERIMENTALI

THE “SEISRACKS2” EU-RFCS RESEARCH PROJECT
“SEISMIC BEHAVIOUR OF STEEL STORAGE PALLET RACKING SYSTEMS” - PART 2: EXPERIMENTAL ACTIVITIES

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ABSTRACT
This is a presentation of the EU research project SEISRACKS2 : “Seismic Behaviour of Steel Storage Pallet Racking Systems”, RFSR-CT-2011-00031, organized into three papers: the first one (part 1) giving a global overview of the project as well as an identification of lacks and weaknesses of the present version of FEM Recommendations and definition of the case studies, the second one (Part 2) dealing with the experimental results achieved to date (Work Packages 2 to 4) and the third one (Part 3) summarizing the numerical studies carried out to date (Work Packages 5 and 7).

SOMMARIO
Questo lavoro intende illustrare il progetto Europeo SEISRACKS2 : “Seismic Behaviour of Steel Storage Pallet Racking Systems”, RFSR-CT-2011-00031. La presentazione è organizzata in tre parti: la prima fornisce un inquadramento del progetto e dei casi studio, ed un’identificazione delle lacune della attuale versione della norma FEM 10.2.08, la seconda parte riassume i risultati sperimentali sin qui ottenuti (WP 2, 3 e 4), e la terza descrive le attività numeriche (WP 5 e 7).
1 WP2 – COMPONENT TESTING

1.1 Tests on beam-to-upright connections

1.1.1 Tests in down aisle direction

Tests were performed aimed to the assessment of the moment rotation characteristic of the beam to upright connections as well as of the influence of loading conditions.

The setup of the down aisle tests is different from the one proposed in EN 15512 (2009) for beam end connector tests, and was developed within the scope of this research project to provide information about the plastic deformation capacity under realistic support and loading conditions.

The test setup represents one shelf of a rack system with a bay width of 2.70 m, commonly used for storage of 3 pallets. The height of the frame is 1.00 m and the beams are installed at half height. To load the rack with pallets two frames – a front and a back frame - are needed. The front frame is made of the rack parts (uprights and beams) to be tested. The uprights are perfectly hinged at the supports and at the top so that the sway of the frame is constrained by the beam to upright connectors only. The back frame is a kinematic frame made of hollow sections with the beam perfectly hinged to the columns (Figure 1).

![3D Test setup](image1)

![Sketch of test setup](image2)

The applied force $F_{applied}$ was imposed by an hydraulic jack. Along with the applied force the reaction forces at the supports of the front frame, the sway of the frame and the rotation of the beam ends were measured during the tests (Figure 2). The payload was applied by loaded pallets, as in a realistic loading situation. Influence of loading on the connector behaviour is investigated by testing the racks with different pay load (0%, 50% and 100% of service load). For each load case and for each producer (4 producers) one monotonic and one cyclic test were performed. Under deformation controlled conditions by means of monotonic push over tests a load deformation curve was generated to derive the control values for the cyclic tests. The cyclic tests were also deformation controlled where the applied deformation amplitudes were related to the reference deformation $e_y$ from the monotonic tests in accordance to the ECCS cyclic testing procedure. One cycle with the amplitude factor 0.25, 0.50, 0.75 and 1.0 and 3 cycles with the amplitude factor 2, 3, 4... were carried out until failure. Tests results provided information related to Failure modes, Influence of payload, Differences between cyclic and monotonic behaviour, Moment rotation characteristic, Compatibility of these test results with those derived from EN 15512 standard tests, Effectiveness of safety bolts.

1.1.2 Tests in cross aisle direction

Tests are carried out for the assessment of the moment rotation characteristic of the beam to upright connectors and of the influence of pallet loads on the cross aisle deformation behaviour of the beams. It is expected that the influence of pallet loads is mainly governed by the friction between
pallet and beam and the stiffness of the pallet. The influence of shear forces transferred from the beams on the behaviour of the beam to upright connection is expected to be low or negligible.

In addition to the test program initially included in the proposal, frictions tests have been performed to allow determining the influence of pallets on the cross aisle deflection resistance. The friction tests were not performed in accordance with FEM-rules (FEM 10.2.08, 2010) where the pallet beams are inclined until sliding of the pallet. In the tests performed here the beams remain in horizontal position while the pallet is moved by a measured external force. This test setup allows for the distinction of adhesive and sliding friction (Figure 3).

![Fig. 3 Setup of frictions tests (left: FEM tests; right: performed tests)](image)

The adhesive friction coefficient is the maximum friction value when the pallet starts sliding while the sliding friction coefficient is the mean value during sliding (Figure 4).

![Fig. 4 Example for derivation of friction coefficients from tests](image)

In total, 27 friction tests were performed on the pallets representing the 50% of the maximum service load (approx. 400kg). The tests started on beams with untouched surface (producer C) and were continued without changing the beams during testing. Pallets were placed on the beams and pulled in longitudinal direction. When the maximum displacement of the displacement transducers was reached the pallet was lifted up and moved backward to the starting position of the next test. It was observed that the friction coefficient on the beams with untouched surface is significantly lower than the coefficient on the scratched surface. Testing started with the 412kg pallet (tests 412kg-1 and 412kg-2). After testing the other pallets the tests on the 412kg pallet were repeated (tests 412kg-3 and 412kg-4). The sliding coefficient of friction increased from 0.34 to 0.49.

Figure 5 summarises the results of the friction tests on pallets with 50% of the maximum service load. The test setup for the cross-aisle specimens represents a typical rack detail with a bay width of 2.70 m. Two pairs of uprights allow the installation of beams that can be loaded by standard pallets.

The end frames are detailed such that one frame is movable while the other end frame is fixed and the reaction forces $R$ are measured. In the tests a horizontal displacement $\delta$ is applied to the movable end frame and the corresponding force $F$ is measured (Figure 6). Additional measures are the transverse rotation of the beam in the connectors, the shear forces $H$ transferred from the uprights to the beams and the lateral displacements $d$ of the beams between the pallets.

The measurement of the rotation angles and the global displacements allow determining the moments in the connectors by application of mechanical rules (Figure 7). The result may be cross checked by comparison with the measured shear forces in the case of unloaded tests. In case of loaded pallets, friction of pallets may influence the deflection of the beams such that mechanical rules for determining the moments do not apply. The change of the deflection line of the beams is determined by the displacement measurement $d_i$ in the gaps between the pallets. Together
with the shear forces $H$, the moments and rotation in the connections it is possible to determine friction effects of the pallets.

![Graph](image)

Fig. 5 Test results pallets with 50% max service load

![Images](image)

Fig. 6: Drawing of setup

Fig. 7 Sketch of test setup

For the tested products it can be stated that the moment resistance in the connectors for cross aisle bending is negligible and pallet friction mainly controls the resistance in the cross aisle direction.

### 1.2 Column-base tests

The column base tests are carried out for the assessment of the moment rotation characteristic of the connection between the upright and the column base. The connection of the base plate to the ground (concrete slab) is not within the scope of these tests to prevent the dowels to be tested instead of the upright to base plate connection. Furthermore, the possible variations of concrete slabs (thickness, reinforcement and strength) on the compression side of the connection and variation of applicable dowels (type and producer) on the tension side of the connection is too large to obtain results that can be transferred to real projects. The characteristics of this part of the connection can be obtained for a specific case application on the basis of the dowel characteristics (provided by dowel producer) and concrete characteristics and easily added to the moment-rotation characteristic from the tests presented here. Figure 8 shows the stiffness and resistance component of the complete base plate connection. The test setup shown in figure 9 represents a column base that is rigidly connected to the floor. On top of the upright there is a steel plate where the horizontal load is applied. To allow for horizontal deflection of the top steel plate a pendulum is installed between the top plate and hydraulic jack that applied the vertical force. The vertical force is controlled to be constant over the duration of the test while horizontal displacements are superimposed by a horizontal hydraulic jack measuring the applied force. Horizontal forces from second order effects are also measured by the horizontal devices. In the
project proposal it was intended to test the column bases in down aisle and in cross aisle direction. Figure 10 shows the difference of the loading of the upright for the different directions: While the down aisle loading causes bending in the base plate connections, loading in cross aisle direction cause mainly normal forces at the column bases as the columns are connected by a framework to one section and the uprights act as flange. Bending in the baseplate connection due to cross aisle bending seems thus to be negligible.

![Figure 8: Components of stiffness and resistance of the fixing upright to slab](image)

![Figure 9: Sketch of principle test setup](image)

2. SUBSTRUCTURE TESTS

Substructure testing is carried out on cross-frames and braced longitudinal frames under horizontal loading, aimed to the definition of standardized procedures for the assessment of the local ductility of cross-frames, of the longitudinal frame bracing properties.

2.1 Cross frames

4 types have been identified based on the geometrical pattern of the diagonals as well as and 4 types of diagonals’ position and connection (see Part 1, figure 1). 8 case-studies have been prepared (2 by each IP plus one extra for one Partner) with the objective of getting a wide range of situations (design for low/moderate/high seismicity, D/Z/X type of cross bracing).

![Figure 10: Directions of rotation and loads on the base plate connection](image)

Tests are presently underway. The total number of tests on the substructures will be:

- for unsymmetrical frames: 3 tests = 2 pushover + 1 cyclic;
- for symmetrical frames: 2 tests = 1 pushover + 1 cyclic;
2 WP 3: WAREHOUSE TESTING

This work package includes the works for operational monitoring of a real warehouse, identification of the linear dynamic properties of racks, and identification of dynamic properties of pallets/merchandize.

2.1 Continuous monitoring of a storage structure

During the previous Seisracks1 project, an installation near Athens has been continuously monitored to record rate of occupancy, operations and accelerations. As the measurement system was still on the site, despite a number of accidents (more or less fortuitous) occurred in the meantime, it has been reactivated in order to obtain data from continuous monitoring during the whole Seisracks2 research. Figure 11 shows the positions of the accelerometers on the rack. Data are recorded continuously on site, and transmitted to the remote server of NTUA via wire-less. Because of the current economic crisis that is causing a drastic reduction in the commercial activities in Greece, also the activities within the warehouse are reduced. It is hence to be expected that less goods are present on the racks, and that, due to the smaller request, also the picking activities are reduced. Despite all this, a large number of data related to everyday activities is being recorded at a 200 Hz sampling rate, and re-analysed. Because of the enormous amount of recorded data, it has been decided to re-analyze only the data related to “significant” events, in which the absolute value of the peak acceleration exceeds 0.05\( \times \)g. With reference to the available “significant” events only, the frequency of occurrence of acceleration peaks was derived (to date), adopting steps of 0.1 g (as shown in figure 12, with reference to the data available to date). Through this type of re-analysis performed on the global set of all recorded data, it will be possible to derive indications on design values of acceleration to be accounted for, in order to keep into account the storage and retrieval (S/R) activities. Furthermore, based on the total number of cycles recorded per year, it will be possible to derive indications about whether or not fatigue problems might affect the racking systems and should be accounted for in the design.

| Fig. 11 Position of accelerometers on the rack | Fig. 12 Frequency of occurrence of acceleration peaks |

For each event, by re-analyzing the acceleration time histories, indications are also derived on the deformation of the structure under impact loading due to the S/R actions, and its modal shapes. The recording activities are presently underway, as well as the re-analysis of the recorded data.

2.2 Identification of the linear dynamic properties of racks on the base of ambient vibration or hammer tests

The warehouse testing presented here aims at identifying the linear dynamic properties of racks on the basis of free response tests. The objective consists in defining the range of periods and damping of a real structure and to calibrate numerical models. These tests are done on site on existing structures in active warehouses chosen by the IPs (one warehouse for
each IP). The geometrical and material properties of the structures to be monitored will be chosen very similar to the case studies of this research. The signals are decoupled in longitudinal and transversal vibrations. It can be assumed that the rack will deform mainly in shear following the vibration modes shown in figure 13.

![Vibration modes](image1)

**Fig. 13** Vibration modes.

To distinguish and measure both vibration modes it is necessary to place the sensors at 2 levels; one at mid-height (level 4250mm) and one on top of the structure (level 8540mm). The warehouse chosen by partner D is divided into 2 parts; one with a lot of fork-lift traffic and another part with goods that are stored for a longer period and where the traffic is reduced. In order not to disturb the activity of the store, it was decided to test a single-entry rack of this second part of the warehouse as shown in the general layout of Figure 14.

The transversal vibrations have been measured in 3 different sections on the length of the structure. The longitudinal measurements have been taken at the same place as for the transversal tests. An additional biaxial sensor has been placed on top of the rack at the same place as the middle mono-axial sensor.

![General layout of the warehouse](image2)

**Fig. 14** General layout of the warehouse.

### 2.2.1 Transversal measurements

The 12th upright was pulled and pushed several times transversally before releasing the impulse and let the structure find its position after absorption of the movement. Several of these free response tests were carried out first at the 2\textsuperscript{nd} level (4.0 m from ground floor) and then at 4\textsuperscript{th} level (8.0 m from ground). Natural frequencies and mode shapes were obtained by stochastic subspace identification method. The results provided by the identification procedure must therefore be scrutinized, case-by-case, for the specific results of each identification. In particular, 3 possible natural frequencies were identified (Table 1) with the corresponding mode shapes. For both types of excitation (2\textsuperscript{nd} level or 4\textsuperscript{th} level), the obtained results are in good agreement (Table 1).

<table>
<thead>
<tr>
<th>Shaking at level</th>
<th>Mode 1 Freq. (Hz)</th>
<th>Mode 2 Freq. (Hz)</th>
<th>Mode 3 Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (4.0 m)</td>
<td>1.49</td>
<td>2.07</td>
<td>2.34</td>
</tr>
<tr>
<td>4 (8.0 m)</td>
<td>1.59</td>
<td>2.01</td>
<td>2.42</td>
</tr>
</tbody>
</table>
The first mode corresponds to an in-phase movement of the 3 measured cross-frames in the same transverse direction. The second mode corresponds to a kind of local torsion in the rack, which can be termed as a “snaking mode”. This mode cannot be understood as a global torsion otherwise it would have resulted in excessive amplitudes at both ends of the rack. The third mode shape is similar to the snaking mode mentioned for the second mode.

2.2.2 Longitudinal measurements

<table>
<thead>
<tr>
<th>Shaking at level</th>
<th>Mode 1 Freq. (Hz)</th>
<th>Mode 2 Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (4.0 m)</td>
<td>0.62</td>
<td>1.87</td>
</tr>
<tr>
<td>4 (8.0 m)</td>
<td>0.60</td>
<td>1.80</td>
</tr>
</tbody>
</table>

Two tests were performed, by shaking (with a fork lift truck) the rack longitudinally at the 2nd and at the 4th level. The forklift pushed the rack away from its rest position in the longitudinal direction before releasing it suddenly. This way of exciting the structure mainly provides a response in the lowest mode. For each level, multiple loading repetitions were performed. The natural frequencies, obtained by stochastic subspace identification method, are shown in table 2.

2.3 Identification of dynamic properties of pallets/merchandize (mass, frequency, damping ratio, sliding properties, sensitivity to rocking)

The dynamic properties (frequency, damping) of a large range of stored merchandizes were identified on the basis of a push-by-hand excitation on top of the stored good with a quick release or an impact given by the human waist. Several such shocks have been given in both directions of the pallets and the vibration and damping have been recorded.

For each of the chosen pallet a tri-axial sensor has been fixed on top of the goods in order to measure the vibrations along both axes (x and y) parallel to the pallet edges. From each signal, natural period and damping ratio are identified for each reference axe, and then averaged to give the “global” property of the pallet.

The natural frequency of the stored goods on pallets varies from 3.25 Hz to 6.21 Hz; the damping ratio varies from 3% to 7%.

3 WP 4: FULL SCALE TESTING

This work package aims to assess the global behaviour of full scale racks in down aisle and cross aisle directions. Specimens for longitudinal tests will be 4 levels (8.0m) and 2 bays (6.0m). For each producer 1 braced frame, and 1 unbraced frame will be tested in down-aisle direction and 1 in cross aisle direction, for a total of 12 full scale push-over tests. Tests will be carried out under force controlled conditions, and forces will be introduced at each level by means of hydraulic jacks having a 100 kN capacity and a 1.0 m stroke.

Full scale testing activities are supposed to start in July 2013.