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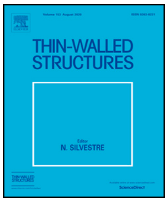

Review

State-of-the-art review on adjustable pallet racks testing for seismic design

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ABSTRACT

This paper presents a state-of-the-art review on seismic tests of adjustable pallet rack systems: on particular components of racks, subassemblies, full racks and stored goods. The tested particular components are the most critical connections: beams-to-uprights, braces-to-uprights, and floor-to-uprights; subassemblies also include beam-to-upright connections, among other components. Tests on full racks can be static (pushover), pseudo-dynamic, or dynamic (pullout and shaking table). Finally, tests on stored goods are sliding (aimed to identify the friction coefficient with the supporting members) and tilting (to check their confinement). The examination of the discussed experiments provides relevant conclusions and allows identifying research needs.

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1. Introduction

Several types of industrial storage racks for goods (products) and materials are commonly used: drive-in/drive-through, adjustable, push-back (back-racking), pallet flow, compact storage, roll-formed cantilever, self-supporting (Automated Rack-Supported Warehouses), hand-loaded shelving, and others [1]. Among them, adjustable racking systems (also known as selective or conventional) are the most spread due to their versatility, simplicity, and economy. This type of rack is a skeleton-type steel-framed structure meant to store goods (ordinarily palletized) in a conventional way. These structures are highly vulnerable to seismic ground motions, mainly due to a lack of lateral stiffness, strength, and energy dissipation capacity; therefore, their earthquake design is a relevant issue. Moreover, their lateral cyclic behavior is rather irregular and becomes difficult to characterize; hence, there is a strong need for experiments oriented to seismic issues. Despite an important testing activity has been undertaken worldwide, this knowledge has not been yet totally incorporated into the daily seismic analysis and design of adjustable pallet racks. Then, this task still involves unsolved questions; as a result, nowadays, it is mostly based on oversimplified and, hence, probably rather conservative approaches. This circumstance highlights the need to perform more tests and improve their regulation in the codes. Given this situation, this paper presents a state-of-the-art review on testing adjustable pallet racks aimed at seismic design. In this context, this article aims to provide a global overview on earthquake-oriented experiments of this type of rack and identify further research needs. Nonetheless, as any experiment on racks provides relevant information regarding their seismic behavior, tests that are not specifically seismic-oriented are briefly summarized too.

Five major types of tests on racks have been reported in the technical literature: (i) coupon tests, (ii) tests on particular parts (components) of racks, (iii) on subassemblies, (iv) on full rack assemblies, and (v) on stored goods. Coupon tests are oriented to obtain the steel mechanical parameters, and are not specific to seismic situations. Regarding experiments on components, such parts are the most critical ones: connections between beams and uprights, braces and uprights, and floor and uprights; subassemblies are commonly 2-D framed structures that include beam-to-upright connections (to avoid confusion, it should be mentioned that some documents consider the connections as subassemblies instead of individual parts or components [2]). Experiments on full racking systems are performed ordinarily in shaking tables, although pullout, pseudo-dynamic, and static pushover tests also exist. In this context, this paper describes the tests (corresponding to these types) carried out worldwide. Finally, sliding and tilting tests of palletized goods are also discussed.

2. Adjustable pallet-rack systems

Adjustable pallet-rack systems are steel structures intended to store goods. “Adjustable” refers to the rack structure (liberty to connect the shelves to any height of the supporting members); “pallet” is the most common support (usually wooden) of the stored products. As shown in Fig. 1.a, pallet-rack systems consist of vertical linear elements (uprights, posts, or columns), horizontal (front and rear beams, or stringers), and sloping (braces, or diagonals, although horizontal braces also exist). The longitudinal horizontal direction is termed as *down-aisle* while the transverse one is referred to as *cross-aisle*. Commonly, all these structural members are made of thin-gauge cold-formed steel profiles. Fig. 1.a shows that racks behave as framed structures in the down-aisle direction. In single racks (“back against the wall”, aisle at the front side), braces in the rear plane are rather frequent (especially in seismic areas) although they might generate relevant eccentricity due to the difference between the stiffness of the front (unbraced) and the back (braced); in double racks (“back against back”, aisles at both sides), spine braces are more common, since there is no such asymmetry. In cross-aisle direction upright frames are used, consisting of a pair of uprights (columns) connected by diagonals to form a vertical braced frame (Fig. 1.a). Finally, in seismic regions, racks are frequently braced horizontally too in order to ensure the rigid diaphragm effect of each ledge (beam level).

Speed-lock beam-to-upright connections are employed to facilitate rack erection, being based on inserting hooks into upright perforations (tabs), as described in Fig. 1.b. Then, to prevent upward sliding of the hooks (due to accidental forces during rack operation), two solutions are commonly considered: spring-controlled safety pin (safety rivets, Fig. 1.b) and bolts (Fig. 1.c). Obviously, the latter provides better safety, but insertion and removal operations become more cumbersome. Finally, fully bolted connections (not speed-lock) can also be considered for heavy-duty racks (bolt-only, Fig. 1.d).

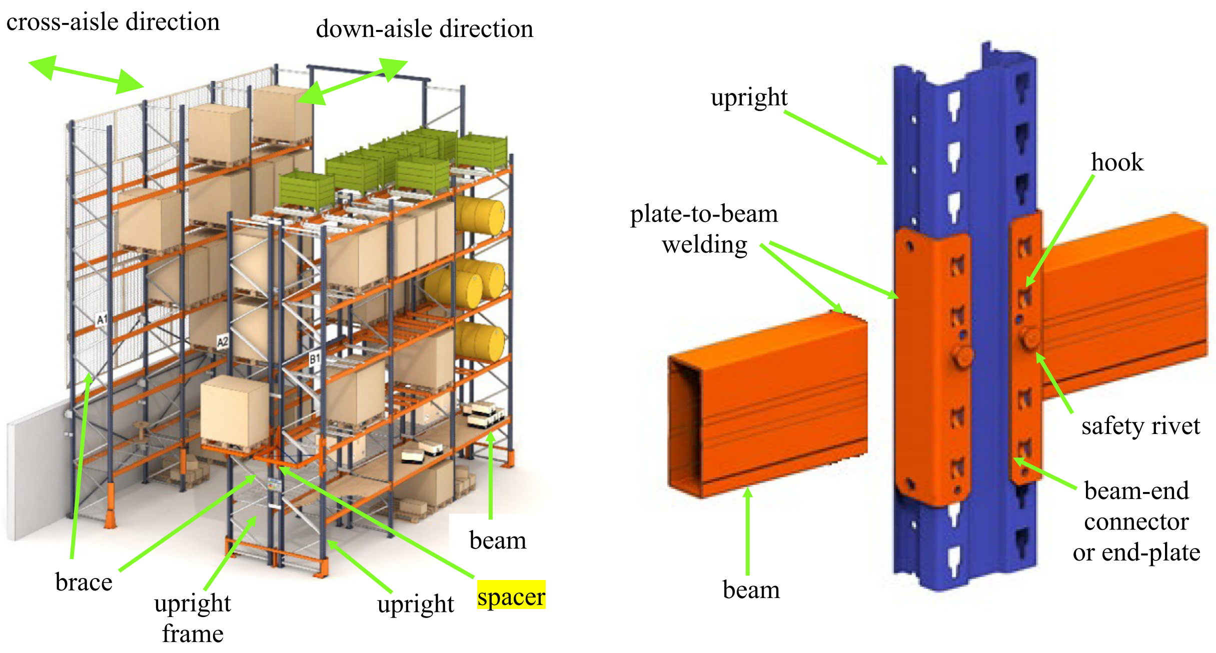
Fig. 2 Displays the other common connections in adjustable racks: floor-to-upright (Fig. 2.a) and brace-to-upright (Fig. 2.b).

The rack foot consists of a steel baseplate (bolted to the ground) which is welded to a C-shaped connecting element (channel); in turn, the foot is bolted to the upright (Fig. 2.a). Other similar configurations of the floor-to-upright connection are also possible (Fig. 20). Brace-to-upright connections are ordinary bolted (Fig. 2.b), although welded connections also exist.

3. Seismic performance of adjustable pallet-rack systems

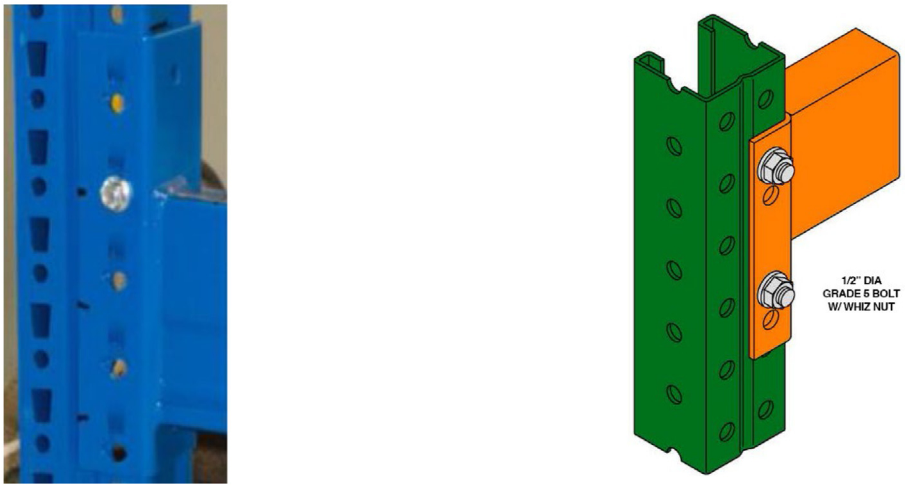
The seismic behavior of racking systems is a significant topic, as they are highly vulnerable, and the seismicity of many sites is also high [3,4]. The vulnerability of racks is principally due to their low lateral strength and stiffness; for that reason, generally, only the horizontal components of the seismic inputs are accounted for. Also, the live load masses are highly variable, randomly distributed, and might slide on the beams; hence, these important uncertainties put off any precise estimation of the modal parameters. This low capacity to horizontal seismic loading is more critical in the down-aisle direction, because of the aforementioned common absence of bracing [5,6]. In addition, as discussed in Section 2, rear braces in single racks can generate harmful twisting unless horizontal braces are introduced to enforce the diaphragm action.

In the down-aisle direction, one of the reasons (although not the only one) for the lateral flexibility is the looseness and low stiffness of the connections between beams and uprights. Fig. 1.b displays such a connection, where two beams are framed to each side of the upright. These beams are welded to L-shaped end-plates connected, in turn, to the upright through several hooks inserted into the upright perforations. As the gap between the hooks and the perforations is necessary, these connections present significant looseness (slippage) and are rather flexible [5], as previously stated. In other words, under down-aisle seismic excitation, the beam-to-upright connections are the most flexible and weakest components; consequently, their stiffness and energy-dissipation capacity are of primary importance to the overall seismic capacity of the rack. Moreover, some structural members (uprights and braces) are of class 4 [7] (i.e. slender, according to American documents), while beams can be either of class 3 or class 4 (semi-compact or slender). Hence, energy dissipation in the main structural



(a) Adjustable pallet-rack

(b) Beam-to-upright connection



(c) Beam-to-upright hooked connection with a bolt

(d) Beam-to-upright bolted connection

Fig. 1. Typical adjustable pallet-racking systems.

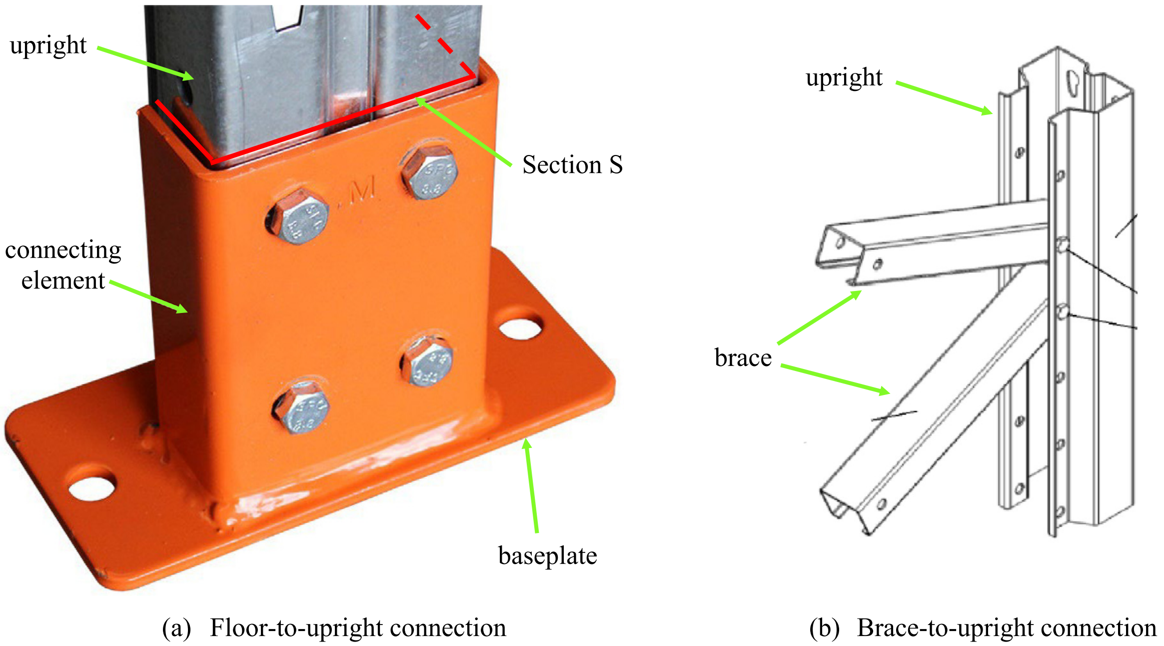
members is not feasible. This tendency causes the rack behavior factor (q in Europe, response modification factor R in American documents) to be established principally in line with the characteristics of the connections.

In the lateral cross-aisle direction, the rack under consideration is potentially more resistant, due to the positive effects of bracing (Fig. 1.a). However, the risk of uplift and even overturning is higher; therefore, the base-to-upright connections might be highly demanded. Besides, the stored products can slide and even fall, causing significant worry. Finally, differential cross-aisle displacements of the upright frames (Fig. 1.a) can generate important demands on the beams and their connections with the uprights.

Given the discussions in the previous two paragraphs, valuable research activity on the seismic design of racks has been conducted worldwide. Broadly speaking, two major methodologies have been proposed for the seismic design of racks, namely dissipative and non-dissipative formulations [8]. In the non-dissipative strategy, little or no damage is admitted; on the contrary, in the dissipative approach, only the global integrity is pursued, and more damage is accepted. In other words, the structures remain in their linear ranges in the non-dissipative formulation, so no energy is dissipated; conversely, the contrary occurs in the dissipative strategy. The major pros and cons of both strategies are summarized in the next paragraph.

Costly rigid and robust structures are obtained using the non-dissipative design approach, whereas the dissipative formulation results in more economical and less robust racks. However, any rack needs to be sufficiently ductile since relevant damage is expected after extremely severe seismic events, thus generating higher repair and replacement costs for the racks designed according to the dissipative philosophy.

The non-dissipative formulation is normally used nowadays in seismic design of racks, feasibly because of their rather low ductility and a certain scarcity of experimental and theoretical studies on their nonlinear behavior (due to its high complexity). In contrast, in the seismic design of civil engineering constructions, the dissipative strategy is almost always considered. This paper is aimed to identify research



(a) Floor-to-upright connection (b) Brace-to-upright connection

Fig. 2. Floor-to-upright and brace-to-upright connections using bolts.

needs whose completion may contribute to promoting the dissipative approach.

4. Standards and other documents on seismic tests on adjustable racks

4.1. Overview

The two main references for the seismic design of racks are the American ANSI-RMI MH16.1 Specification [9] and the European Norm EN 16681 [10]; ANSI-RMI MH16.1 [9], is not mandatory, while EN 16681 [10] is a formal Standard for all the European member countries.

The first seismic design provisions were introduced in America in 1972 by the Rack Manufacturers Institute (RMI) when earthquake loads were included in the second edition of the RMI Specification. Soon after, in the 1970s and early 1980s, the first relevant studies on the seismic behavior of steel storage racks were carried out by Blume et al. [4], who provided basic information for the development of the Specification. Since then, RMI has made an effort to align with the racks research and the main recommendations, codes, and standards concerning seismic design (IBC, NEHRP, ASCE/SEI-7 and FEMA 460). Refs. FEMA 460 [2] and Castiglioni [4] and the Commentary on the different editions of the RMI Specification may be very useful to know its evolution. It is noted that the first cyclic test was included in the 2008 edition [11].

The development of a European standard for seismic design of steel storage rack systems was initiated in 2000 by the European Racking Federation (ERF) [4]. The starting points were the Eurocode 8 [12] and the Rack Manufacturers Institute (RMI) Specification [11], in use at that time. The first result of the ERF work was [13], which over the years evolved into the current standard [10]. Two European-funded projects have contributed significantly to develop this new norm: SEISRACKS [4,14] and SEISRACKS 2 [3]. The background to the experimental tests presented in this section, as well as some criticisms and alternative approaches, can be found in the final reports of these projects.

China also has an important tradition on design standards for racks: CESC 23 [15] and GBT 28576 [16] are oriented for general design of racks, while the most recent [17] is specific for seismic design of racks. Ref. Zhao et al. [18] reports on the performed research.

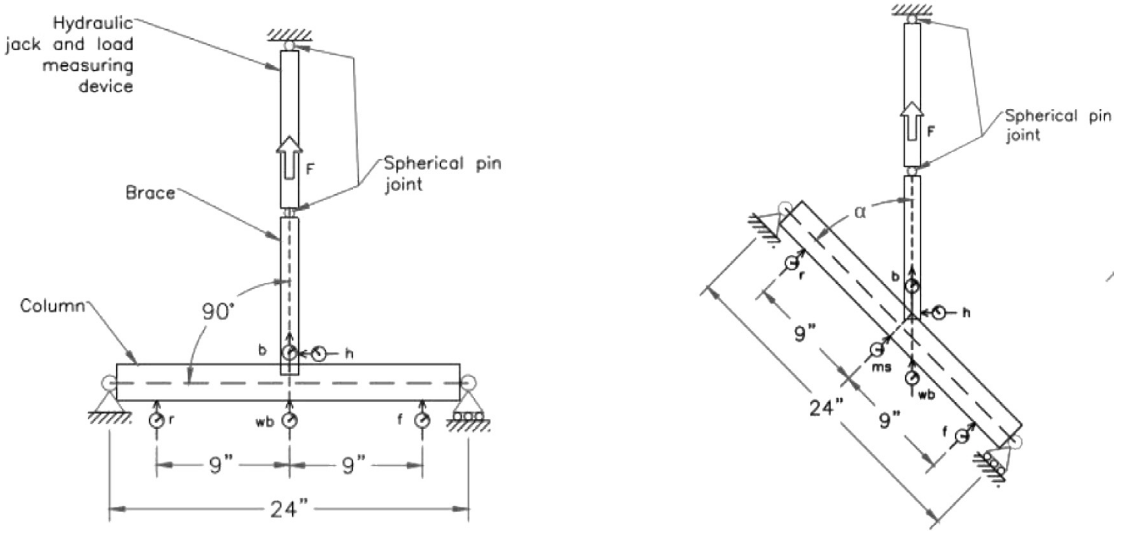
Section 1 has already introduced the types of structural experiments on racks found in the standards and similar documents mentioned in the previous paragraphs [19]. In the following sections, a more in-depth discussion on those tests involved in seismic design is presented. Before, however, the code tests on beams and uprights, which are not specifically oriented for seismic behavior, are briefly summarized:

- ANSI-RMI MH16.1 [9]. This regulation contains prescriptions for upright and beam testing. The objective of the upright tests is to determine their effective section area and investigate the effects of perforations on their local ultimate capacity. These experiments consist of ordinary compression tests of stub columns (segments of uprights); the axial load shall be applied by flat plates against the milled ends of the column. The local buckling factor shall be determined by ordinary stub column tests. Beam tests are intended to determine flexural behavior patterns and parameters, such as the yield and ultimate moments, and the effective flexural stiffness. In these tests beams can be either simply supported or connected to an upright frame; the experiments on a pin-ended beam consist of a classical four-point bending test.
- EN 15512 [7]. In a similar way to ANSI-RMI MH16.1 [9], this norm regulates experiments on stub columns (short segments of uprights) and uprights, to obtain their effective area. The works [20,21] report on upright tests. Oppositely to ANSI-RMI MH16.1 [9], this regulation includes compression tests of upright frames. Moreover, likewise the American standard, this code includes a bending test on a pair of beams connected to their corresponding frames; the objective is to measure their bending strength.

4.2. Prescriptions and recommendations on testing of brace-to-upright connections

The prescriptions for this type of test are included in [9]; their purpose is to determine the axial stiffness and strength of joints between upright frame columns and braces. Fig. 3 displays two examples of testing mockups and fixtures; in Fig. 3.a, the tested brace is orthogonal to the column stub, while in Fig. 3.b both elements form an angle α (Fig. 1.a).

Fig. 3 shows that the brace-to-upright joints are only axially loaded. Monotonic (both compression and tension) and cyclic (seismic) tests are



(a) Brace orthogonal to the upright (b) Oblique connection

Fig. 3. Braces test setups [9].

contemplated; for the latter, the loading cycles are defined in [9]. The out-of-plane displacement is restrained to avoid undesired 3-D effects.

EN 15512 [7] defines a shear test on upright frames with a similar objective: to obtain the axial stiffness and strength of the connection between the lacing and the upright. Contrarily to bracing experiments of ANSI-RMI MH16.1 [9], this test is only monotonic and is not specifically seismic; nonetheless, their results are also necessary for the seismic design.

The works [22–24] report on tests involving braces of rack frames. Also, the papers [25,26] present experiments on recently developed CFS bracing elements that might increase the seismic response of steel storage pallet racks.

4.3. Prescriptions and recommendations on testing of beam-to-upright connections

The conditions for seismic experiments on particular connections between beams and posts (uprights or columns) in the down-aisle direction are discussed in [9,10]. Also, Castiglioni et al. [3] refers to tests in the cross-aisle direction (discussed in Section 4.5 since they are actually performed on subassemblies).

The American regulation [9] indicates that different testing mock-ups shall be considered for monotonic and cyclic experiments. The former is carried out on a specimen consisting of a column stub and a cantilever beam segment connected to one of its sides (Fig. 4.a). The latter is performed on a similar specimen, but with two cantilevered beam segments connected to both of its sides (Fig. 4.b), where the end sections of beams and uprights shall coincide or mimic the points of inflection during seismic shaking. The objective of the monotonic cantilever test is to determine the connection moment capacity, while the beam-to-upright cyclic test is a qualifying experiment for seismic areas.

Fig. 4.a shows that, in the monotonic tests, the vertical driving force is applied downward (hogging) near the end section of the beam.

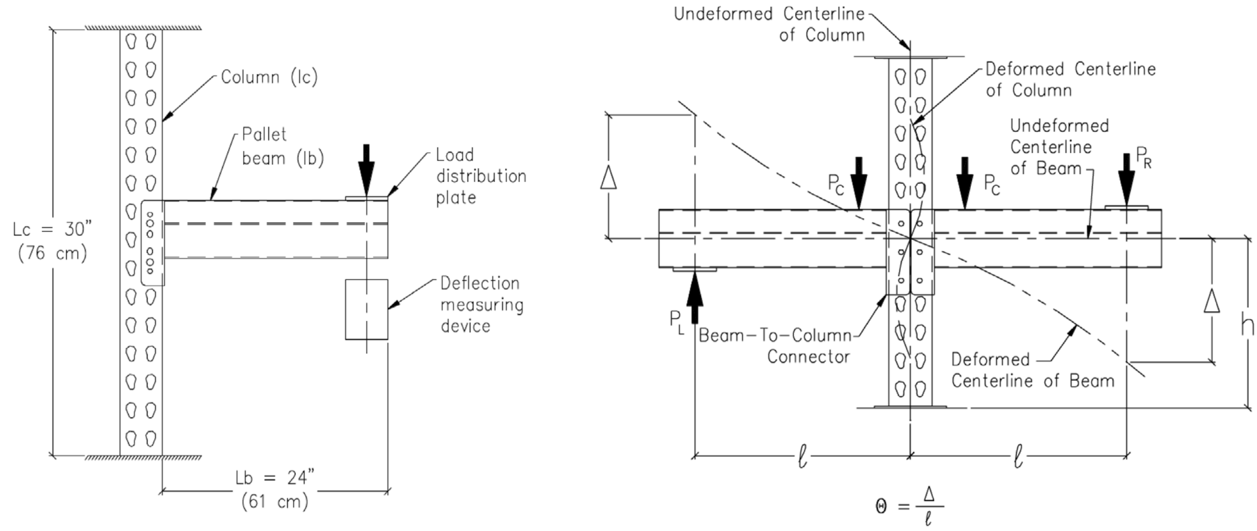
In the cyclic tests (Fig. 4.b), P_C is a constant downward force of 1 kip (4.45 kN) and P_R and P_L are variable alternated forces. P_C represents the gravity loads and also serves to fully engage the beams and their connectors into the column; the alternate condition of P_R and P_L reproduces the actual cyclic behavior in case of lateral seismic excitation. Growing cyclic loading shall proceed with the imposition of equal (although opposite) vertical displacements at each beam end, and the measurement of the forces (P_R and P_L) that correspond to each such displacement. The number and amplitude of the loading cycles are established in terms of angle θ (Fig. 4.b); such amplitude does not depend on the characteristics of the connection, and will increase until failure.

In the tests shown in Fig. 4, as in brace tests of (Fig. 3), any relevant transverse displacement shall be prevented by appropriate bracing.

The seismic tests on beam-to-upright are also regulated by EN 16681 [10] (Annex G, bending tests on beam-end connectors). Down-aisle connections are tested with the primary purpose of determining their rotation capacity when a dissipative design is considered (q factor greater than 2). Down-aisle moment-resisting frames can be designed according to either the low dissipative or the dissipative concepts (Section 3). When a low dissipative concept is considered, a behavior factor equal to 1.5 can be assumed provided that a 1.5 increase factor is applied at the calculated bending moments of the base floor connections. Even using a low dissipative approach, the q factor can be increased to 2 if additional conditions concerning the member section class and design, and behavior of the connection are fulfilled [10]; in that case, cyclic tests are not needed, and the connections can be merely characterized by means of the monotonic tests indicated in [7].

If design according to the dissipative concept ($q > 2$) is applied, EN 1998 [12] should be followed with some specific additional rules [10]; among them, experiments shall support the strength and ductility under cyclic loading of the connections. Accordingly, EN 16681 [10] proposes a protocol for cyclic testing of beam-to-upright and base connections. The test setup and procedure are similar to those presented in [7], Fig. 5.

Changes with the testing description in [7] are only introduced in the loading protocol (see also [27]): (i) test shall be performed in displacement control, (ii) the load jack should impose upward and downward displacements (as to induce reversed moments in the connection), (iii) an additional vertical and constant load of 5 kN (similar to the value PC of ANSI-RMI MH16.1 [9]) should be applied in the upright-beam test to simulate the effect of the unit load (and to approximate the ratios between shear force and bending moment in connections of actual racks during seismic shaking), and (iv) a particular cyclic loading sequence should be imposed. Contrarily to ANSI-RMI MH16.1 [9], this loading sequence depends on the characteristics of the connection; the level of moment and rotation to be reached in each cycle is derived from the design bending strength of the connection and its corresponding rotation obtained in a preliminary monotonic test (see [10] for more details). The acceptance criteria for dissipative design are



(a) Single cantilever setup for monotonic tests

(b) Double cantilever setup for cyclic tests

Fig. 4. Beam-to-column testing setups [9].

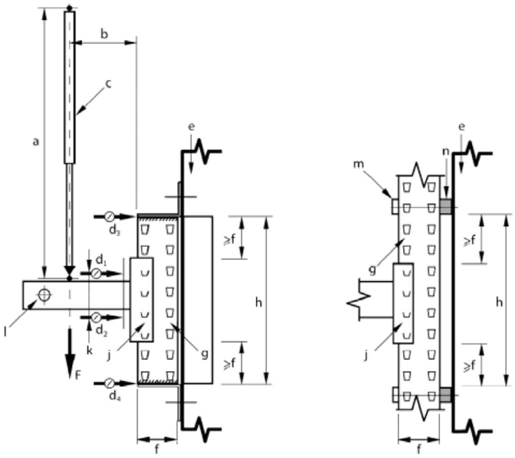


Fig. 5. Beam-to-column testing setup [7].

taken from [12]. Primarily, it must be ensured that the connections have a sufficiently high rotational capacity (see [12] for acceptable values), which should also be consistent with the deformations resulting from the overall analysis of the structure. It is worth mentioning that the cyclic loading protocol of EN 16681 [10] is not used by designers or researchers; instead of it, ECCS 45 [27] recommendation (for general steel connections) is routinely considered. As mentioned in this paragraph, the elastic cycle bounds of EN 16681 [10] are defined in terms of the design moment instead of the yield rotation; this causes several yielding before the onset of the plastic cycles. This issue should be revised in future versions of EN 16681 [10].

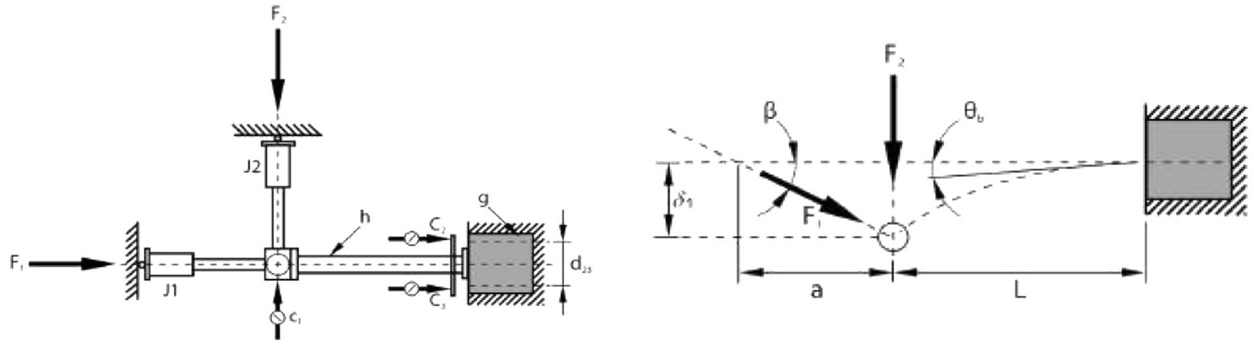
In SEISRACKS project, it is reasoned that beam-to-upright connection tests performed with displacement controlled conditions, as described above, fail to reproduce the real behavior of the connection when the beam supports gravity loads (from the stored products) while subjected to an earthquake dynamic excitation. Then, an alternative loading protocol is proposed by combining segments under force control, to simulate the effect of the gravity load, and segments under displacement control, to reproduce the seismic influence [4]. Additionally, SEISRACKS 2 project proposes an alternative test setup for the beam-to-upright test where a one-bay frame is tested (Section 4.5). According to the project researchers, the new test setup allows considering the beneficial effect of the redistribution of moments. Another relevant general criticism presented in SEISRACKS 2 project to the EN 16681 [10] is that it does not provide any cyclic protocol for tests of cross-aisle upright frames. In this sense, the cyclic test for the upright frame bracing connections presented in the latest version of the RMI Specification [9] represents an improvement.

4.4. Prescriptions and recommendations on testing of floor-upright connections

Base-to-upright (Fig. 1.b) and beam-to-upright connections (Fig. 2.a), are virtually the only sources of ductility of pallet racks; however, the seismic tests of baseplates receive little attention. The prescriptions are included in [9]; their aim is to obtain the base fixity parameters (ultimate and design moments and rotations) of rack columns for given axial loads (Fig. 2.a). Fig. 6.a contains a sketch of such a test and Fig. 6.b represents the forces involved. Notice that these experiments are not specifically seismic; their specifications are coincident with those of EN 15512 [7], except that EN 15512 [7] considers an additional testing method (Fig. 7).

In Fig. 6, the shadowed rectangles stand for the supporting floor, and the adjoining element is the tested column stub; the other two elements hinged to the upright are intended to convey the applied forces F_1 and F_2. Regarding those forces, F_1 represents the constant column axial load, and F_2 is the variable driving force. Tests shall be conducted for several levels of force F_1, ranging between 10% or 25% of the column design load and its total value; such design load is calculated as half of the nominal yielding load times the local buckling factor ($\leq$1). The base rotation is measured by the longitudinal transducers C2 and C3 (Fig. 6.a); the stiffness is the quotient between the moment at the floor (F_2 L) and the rotation. As the moment is computed in the floor, these transducers should be as close as possible to the concrete block [EN-15512 2009]; nonetheless, in occasions, the baseplate device can cover a long segment of upright and can be rather stiff (Fig. 2.a). For those cases the rotation is commonly measured in section S (Fig. 2.a); this section is too far from concrete and can lead to incorrect computations of the stiffness. Future research is required to clarify this open issue.

In the test performing, two options are foreseen: (i) in order to represent the behavior for constant axial loading, the value of F_1 cos β (Fig. 6.b) is kept constant, (ii) both the load perpendicular to the



(a) Testing setup and fixtures (b) Involved forces during testing

Fig. 6. Column base fixity testing [9].

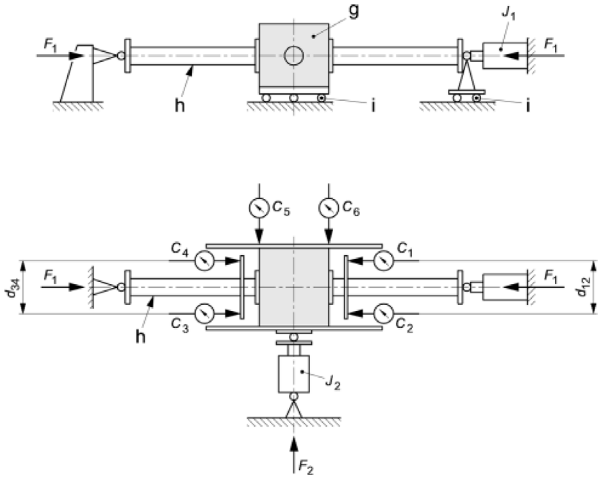


Fig. 7. Column base testing setup [7].

baseplate and the bending moment at that plate shall be increased monotonically. In both cases, the main output of the experiment is the ultimate bending moment for the column base (the maximum moment that can be reached).

EN 16681 [10] also regulates the seismic tests on floor-upright connections (Annex G, bending test on floor connection). As in the experiments on connections between beams and columns, the test mockup is based on general standard [7] (Fig. 7).

For base connection experiments, modifications similar to beam-to-upright are proposed in [10]. EN 15512 [7] also presents a testing setup analogous to the scheme in Fig. 6.

SEISRACKS 2 [3] does not consider the connection between the baseplate and the ground (concrete slab), but focusses on the connection between the upright and the baseplate. Both horizontal directions (down-aisle and cross-aisle) are considered. In the down-aisle direction, the seismic effects at the base consist mainly of bending, while in the cross-aisle direction such effects are mainly represented by normal (vertical) forces; the proposed mockups are displayed in Fig. 8.a and .b, respectively.

For the down-aisle direction (Fig. 8.a), the test setup represents a column base rigidly connected to the ground. On top of the upright, a horizontal hydraulic jack applies controlled displacements to a top steel plate. Another hydraulic jack applies a constant vertical force through a pendulum to allow for the horizontal displacement of the top steel plate.

For the cross-aisle direction (Fig. 8.b), the test setup is similar with three major differences: the vertical force is not constant but cyclic (up and down around the gravity load), there is no horizontal force (it would cause excessive bending), and the base support is inclined (to provide moderate bending).

4.5. Prescriptions and recommendations on testing of subassemblies

Two types of subassemblies experiments on beam-to-upright connections are mentioned in SEISRACKS 2 research project [3]: cross-aisle and down-aisle directions. Figs. 9 and 10 depict the testing setup for both tests, respectively.

Fig. 9 shows that the test mockup consists of a 3-D frame. Only the front 2-D frame is pushed (by a hydraulic jack); the rear 2-D frame lacks any lateral stiffness, and only provides transverse bracing.

Fig. 10 shows that the test mockup also consists of a 3-D frame; only the left upright frame is pushed (by a hydraulic jack), and the right one is intended to remain basically motionless. The behavior of the two connections between beams and uprights is tested in the transverse (cross-aisle) direction.

Castiglioni et al. [3] reports on tests in cross-aisle direction in order to verify the efficiency of the longitudinal bracing under cyclic loading (Section 2) and characterize the brace-to-upright connections. Finally, Castiglioni et al. [3] also describes cyclic and pushover tests on different types of cross frames (upright frames, Fig. 1.a); obviously, such experiments are performed in the cross-aisle direction.

4.6. Prescriptions and recommendations on pushover testing of full racks

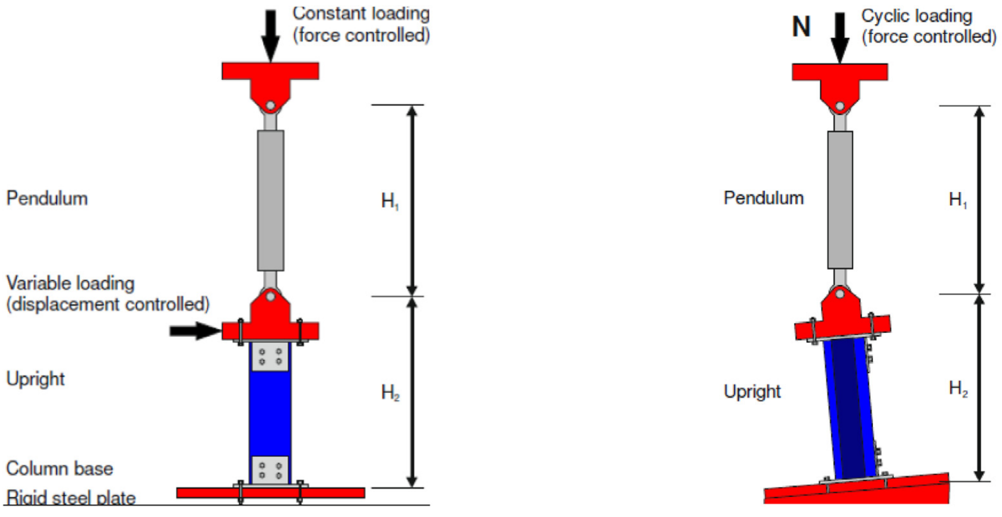
A first step in studying the global seismic behavior on racks consists in performing static pushover tests. In these experiments, lateral forces on each level are representative of the seismic action, and are increased (keeping the same proportion between them) until failure. Full-scale pushover tests are described in [3]. Fig. 11 displays the main characteristics of the experiments.

Fig. 11.a shows that the rack is pushed (or pulled) at all levels by only a single hydraulic jack supported on a rigid structure (commonly known as reaction wall). The jack force is distributed on each level according to a prescribed pattern, Fig. 11.b; in Fig. 11.b forces are proportional to height.

Noticeably, these experiments do not account for any dynamic effect (such as damping, goods sliding or low cycle fatigue). Nonetheless, they provide relevant information about which structural parameters influence most the ductility of racks.

4.7. Prescriptions and recommendations on pseudo-dynamic testing of full racks

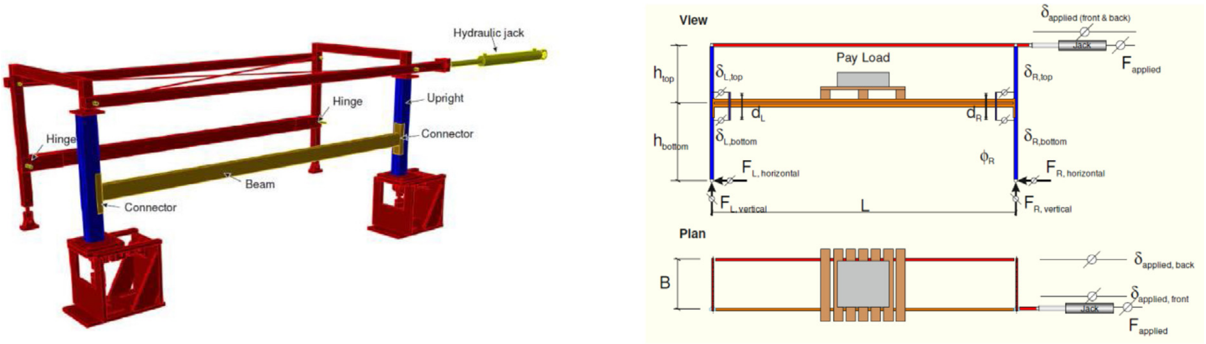
SEISRACKS project [4] describes the performed pseudo-dynamic tests. Such experiments, despite their name, are actually static, and consist of simulating the dynamic behavior of racks without using any shaking table (or similar source of actual dynamic excitation); the



(a) Down-aisle direction

(b) Cross-aisle direction

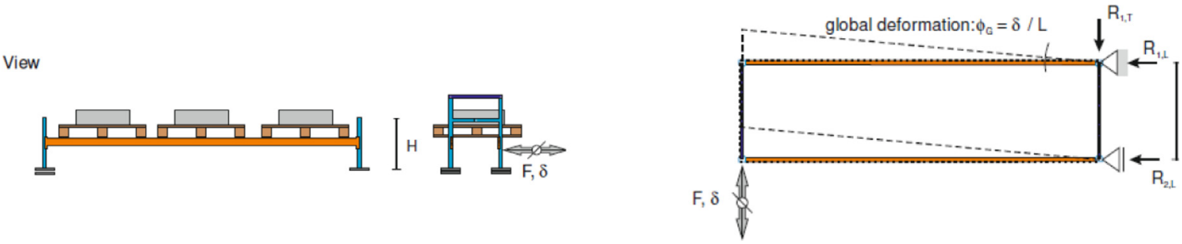
Fig. 8. Testing setups for base connections [3].



(a) 3-D view

(b) Front view and elevation

Fig. 9. Subassembly testing setup in cross-aisle direction [3].



(a) Front and side views

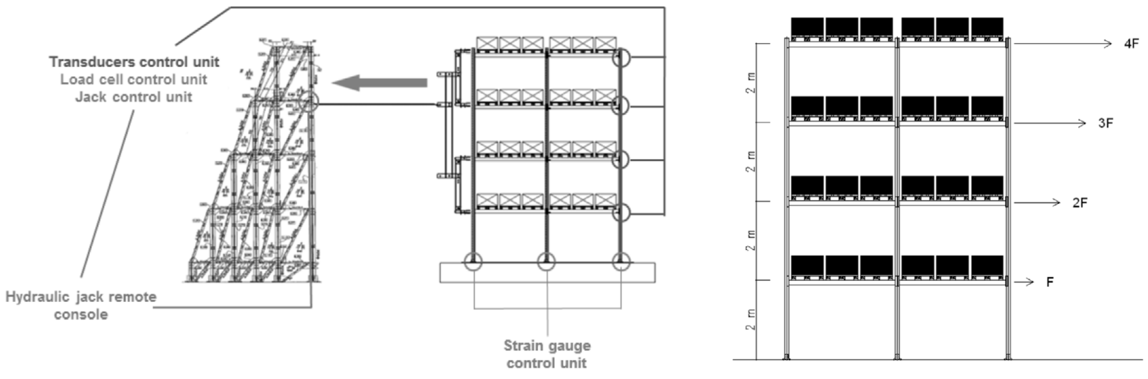
(b) Plan view

Fig. 10. Subassembly testing setup in cross-aisle direction [3].

pseudo-dynamic and pushover setups are similar (Fig. 11), although, obviously, the force on each level must be individually selectable. The duration of the excitation is divided into a number of time steps; in each of them, the dynamic behavior of the tested rack is numerically simulated by a lumped-mass model that accounts for the mass and damping terms. In each time step, the stiffness term (restoring forces) is imposed on each level of the tested rack by a set of hydraulic jacks; obviously, the actual duration of the experiments is much longer than that of the seismic excitation. Fig. 12 schematically depicts the procedure for this type of test.

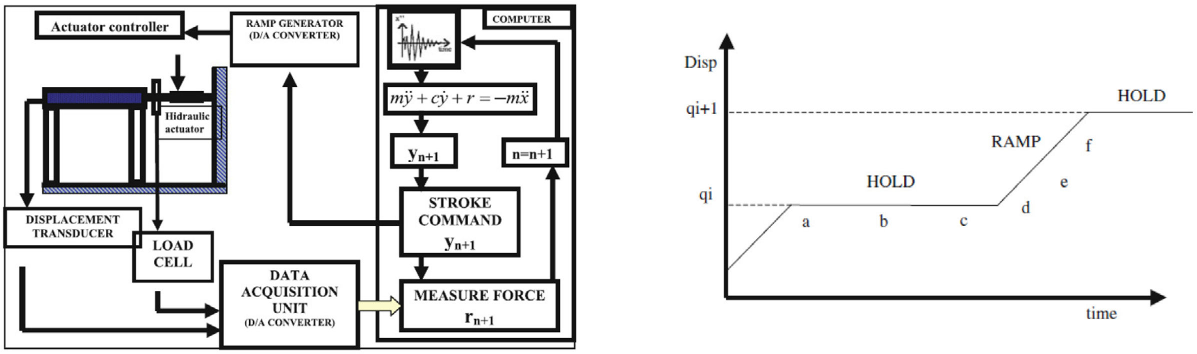
Fig. 12.a shows the algorithm to compute the displacement of the actuators in the pseudo-dynamic method for each load level described in Fig. 12.b: the displacement of the next RAMP phase is approximately computed by integrating the equation of motion, the actual values used in the equation are obtained by sensors during the HOLD phase (it lasts only some milliseconds, in order to avoid structural relaxation, and subsequent loss of load carrying capacity). During the HOLD phase, actuators are still.

Compared to fully dynamic shaking table tests (Section 4.9), the pseudo-dynamic experiments have the advantage of simplicity and lower cost; conversely, the inherently dynamic issues (damping, pallets sliding, rate-dependent behavior, among others) cannot be straightforwardly reproduced.



(a) Test mockup (b) Load pattern

Fig. 11. Push-over test [3].



(a) General algorithm (b) Loading steps

Fig. 12. Pseudo-dynamic testing procedure [4].

No information on other pseudo-dynamic experiments on racks has been found in the technical literature.

4.8. Prescriptions and recommendations on pullout testing of full racks

This experiment consists of pulling the top level of a rack and releasing it in order to analyze its dynamic free motion; they are also known as pull-release or pull-back. This type of experiment is not mentioned in any regulation or similar document; Section 7.2 describes the reported experiments.

4.9. Prescriptions and recommendations on shaking table testing of full racks

This experiment (also known as shake table) consists of simulating the dynamic effect of an earthquake on a racking system by fixing it to a rigid platform (table), and driving that table (commonly by means of dynamic hydraulic jacks) to replicate any desired seismic motion. There are shaking tables with different numbers of dynamic degrees of freedom: one (horizontal), two (horizontals), three (two horizontals and one vertical) and even six (three translations and three rotations). Documents [3,10] mention this type of tests, although no specific indications are reported; Section 7.2 discusses the published experiments.

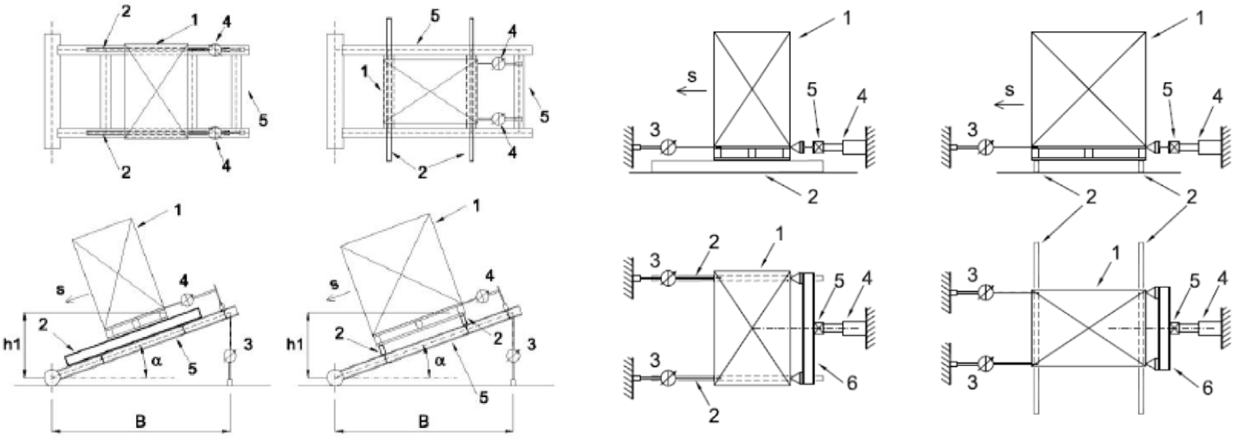
4.10. Prescriptions and recommendations on in-situ dynamic testing of full racks

Document [3] describes three types of in-situ (at the warehouse) identification experiments on actual racks; their objective is to determine the modal parameters (natural frequencies, modal shapes and damping ratios). The first experiment consists of instrumenting a racking system in a seismic area and recording the dynamic response to forthcoming seismic ground motions; the second and third experiments consist of racks excited by ambient vibration (cultural noise) or by hammering. In a similar manner, the paper [28] also finds the modal characteristics of existing racks. The proposed method combines experimental results with extensive numerical analyses. This is especially useful for those racks that have been in-service for decades and require evaluation of their load carrying capacity in accordance with the current design provisions.

4.11. Prescriptions and recommendations on pallet sliding testing

EN 16681 [10] proposes two tests in Annex B to determine the friction coefficient between the pallet and the supporting beam in cross-aisle and down-aisle directions; a single value for both static and dynamic situations is used. In SEISRACKS project [4,14], it was observed that the sliding of the loaded pallet (unit load) is one of the effects governing the dynamic behavior of rack structures. On the one hand, the energy dissipation produced by sliding reduces the seismic action and limits the horizontal inertia forces that can be transferred from the pallet to the beams. On the other hand, sliding is a key factor when assessing the pallets falling risk. Fig. 13.a and b display the two aforementioned test setups proposed by EN 16681 [10] to determine the friction coefficient.

In the frame lift test (Fig. 13.a), the sliding base is lifted on one side while the opposite is pinned to the ground; lifting is continued until the unit load begins to slide. In the push–pull test (Fig. 13.b), the unit load is pushed or pulled in any horizontal direction.



(a) Frame lift test arrangement (b) Push-pull test arrangement

Fig. 13. Pallet sliding tests [10].

Fifty repetitions of the test on the same pallet and beam have to be carried out to obtain 40 values of friction coefficient (the first ten results are not considered because they are not representative of the common actual rack conditions). The tests should be carried out three times, using different specimens (pallets and beams). The final outcome of the tests is the mean friction coefficient μ_S and two additional coefficients $C_{\mu L}$ and $C_{\mu H}$, which can be used to get the statistical lower and upper limit, respectively, of μ_S. EN 16681 [10] provides default values of μ_S, $C_{\mu L}$ and $C_{\mu H}$ for specific materials in contact (steel beams and wood, plastic and steel pallets). However, tests should be carried out for accurate values and other contact conditions. All these parameters are used in different parts of EN 16681 [10]:

- Calculation of the E_{d1} modification factor. μ_S is used to determine E_{d1}, which is a factor modifying the design spectrum to account for the positive effects of sliding. In SEISRACKS project, this factor was observed to range between 0.2 and 1. The values that result from the E_{d1} equation proposed in [10] range from 0.4 to 1, depending on the friction coefficient, the seismic intensity and the structure vibration period. A value of 1 should be considered if any system is applied to restraint the movements of the unit loads. It is noted that the American RMI Specification [9] does not propose a specific test to measure the friction coefficient, and a constant mass modification factor of 0.67 is applied to the stored goods.
- Calculation of the inertial force causing sliding. The product $\mu_S \cdot C_{\mu L}$ is used to determine the value of the inertial force on the unit load that provokes sliding. If the actual inertial forces are higher, the pallet sliding and consequent falling effects should be assessed.
- Calculation of the maximum horizontal action per unit load on the beams. The product $\mu_S \cdot C_{\mu H}$ limits the horizontal force when designing the beams; no higher horizontal forces should be considered.
- Bracing effects of the unit loads. The coefficients μ_S and $C_{\mu L}$ are used in different parts of the norm concerning the horizontal bracing introduced by loaded pallets.

4.12. Prescriptions and recommendations on tests on palletized products

EN 16681 [10] Annex H describes a type of experiment (tilt test, Fig. 14) to assess the strength and stability of the unit load under seismic excitation; as well, recommendations on the aspect ratio of the palletized good are provided for different heights of its location in the rack.

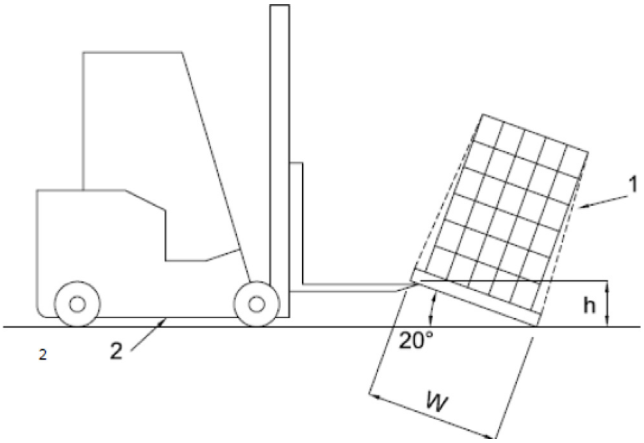


Fig. 14. Tilt test [10].

Fig. 14 shows that the pallet is tilted 20º; this position is held for at least 5 min. If the merchandise remains in place (without appreciable movement) during this time, the test is passed.

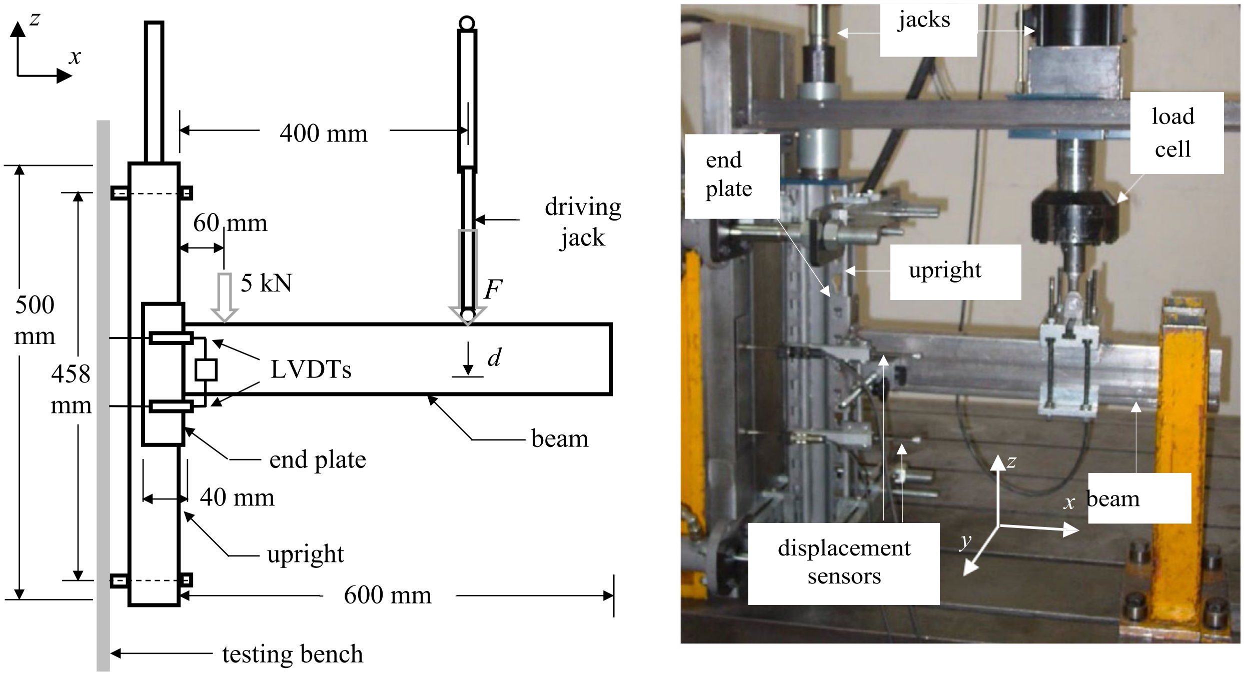
Apart from the tilt test, EN 16681 [10] recommends that the ends of a longitudinal row of racks have upright frames or frame extenders in the uppermost level to provide sliding restraint.

Finally, Castiglioni et al. [3] describes the experimental dynamics parameters identification of the palletized goods (natural frequency and damping ratio). The excitation consisted in pushing manually on top of the stored good, with quick-release or an impact given by the human waist.

5. Tests performed on beam-to-upright connections

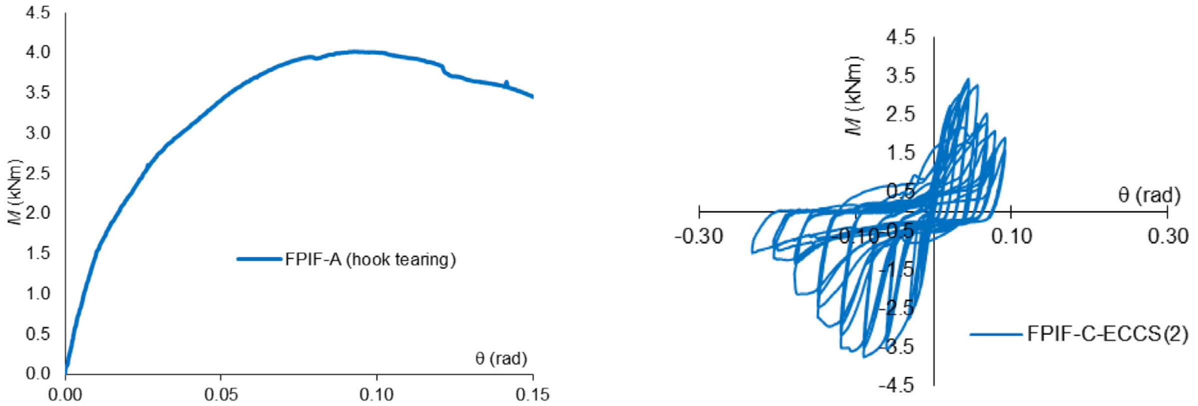
As discussed in Section 1, tests on connections between beams and uprights can be performed either on individual connections (Section 4.3) or subassemblies (single-story single-bay frames, Section 4.5) including such connections; both types of tests are included in this section. Fig. 15 displays a sketch and an image of a typical testing arrangement.

Fig. 15 refers to a testing mockup similar to the one in Fig. 5; the main difference is the constant force of 5 kN. The main measured quantities are the driving force in the jack and its vertical displacement. For the monotonic experiments, the most meaningful results are moment–rotation (or force–displacement) curves; for the cyclic tests,



(a) Sketch of a test specimen (b) Image of a test setup

Fig. 15. Individual single-cantilever tests of beam-to-upright connections [29,30].



(a) Moment-rotation laws for monotonic tests (b) Hysteresis loops for cyclic tests

Fig. 16. Main typical outputs of tests of beam-to-upright connections [29,30].

such plots become hysteresis loops. Fig. 16 presents typical examples of such results.

Fig. 16.a shows a linear elastic branch at the beginning, followed by yielding (near-horizontal branch) and later by failure (decreasing branch). Given that seismic shaking is basically an indirect action (imposed displacement), the displacement ductility is a highly meaningful parameter (ordinarily defined as the ratio between the yielding and ultimate displacements). Fig. 16.b shows a significant encompassed area (absorbed energy, also understood as ductility) and an important pinching; the latter is an undesired effect, as relevant lateral displacements appear without any significant dissipated energy. The stiffness and strength degradation can also be seen in the loops in Fig. 16.b.

Fig. 17 displays the most common failure modes; Fig. 17.a shows tearing in the hooked assembly and Fig. 17.b presents a brittle welding failure between the end-plate and the beam.

Several previous test campaigns on this issue have been reported. The most relevant and recent studies are listed and discussed next:

- Krawinkler et al. [31]. This experimental study consisted of monotonic and cyclic tests of particular elements (components) such as beam-to-post and frame-to-floor connections, subassemblies (frames), and lateral pushing tests of full rack assemblies. Despite the earliness of this research, several relevant conclusions were obtained: (i) the elements that control the seismic response are the beam-to-post and frame-to-floor connections, (ii) beam-to-post connections can be characterized by cantilever tests, (iii) the determination of the response characteristics of posts and upright frames will require tests of full racks, (iv) the P-Δ effect greatly affects the lateral response in the longitudinal (down-aisle) unbraced frame direction, (v) the hysteresis loops of beam-to-post connections have a pinched shape, (vi) low cycle fatigue phenomena (early fracture at welds or points of stress concentrations) may affect the strength and ductility of beam-to-post and post-to-floor connections, (vii) the ductility and energy dissipation capacity of racks is much larger in the longitudinal

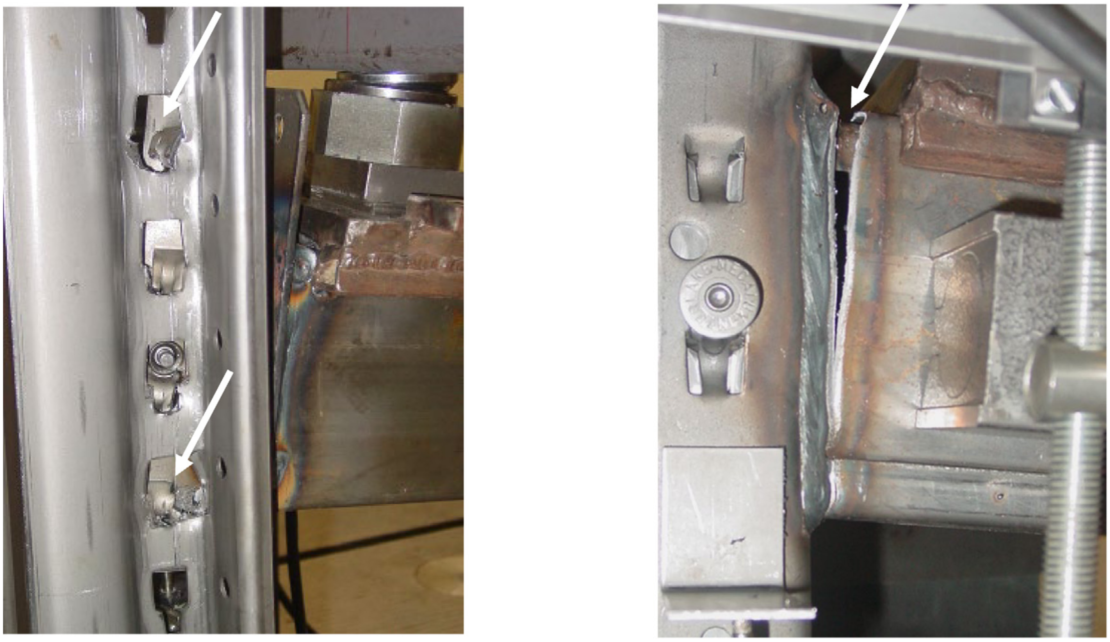

(a) Hooks and perforations tearing (b) Weld break

Fig. 17. Typical failure modes in the cyclic tests [30].

direction than in the transverse one, and (viii) the ductility of the longitudinal frames depends strongly on the ratio between the demanding and the buckling loads.

- Markazi et al. [32]. Cyclic tests on a number of commercially available boltless connections are described. Several interlocking arrangements between the end-plate and the upright are considered: tongue and slot, blanking design, stud-incorporated design, and dual integrated tab. Relevant conclusions are listed and interpreted.
- Bernuzzi and Castiglioni [33]. Hogging and sagging monotonic tests and constant-amplitude up-to-failure cyclic experiments are described; 11 tests have been executed on two commercial products. Important pinching is detected; however, relevant energy dissipation capacity is found. The authors repeatedly highlight the absence of seismic design specifications, except those of the Rack Manufacturing Institute.
- Abdel-Jaber et al. [34]. Monotonic and partially cyclic tests are performed on cantilever beam-to-upright connections and subassemblies (frames). It is mentioned that the flexibility of the used stub beam can induce errors of up to 4% to the moment–rotation relationships; appropriate correction equations are derived.
- Sleczka and Kozłowski [35]. Double cantilever monotonic sagging tests were performed on several beam-to-column connections. The component method was used to assess the moment resistance and initial stiffness of storage rack joints. Results obtained using the developed model were satisfactorily compared with the test results.
- Gilbert and Rasmussen [36]. This research report describes several types of experiments: beam-to-upright connections (tests on subassemblies), base-to-floor connections (rotational and uplift stiffness tests), upright frames (shear stiffness tests, Fig. 1.a), and individual uprights (four-points bending tests). Only the first ones are discussed in this section, while those dealing with baseplates are dealt with in Section 6. The tested beam-to-upright connections are bolted and correspond to drive-in and drive-through storage racks. The experiments are cyclic; therefore, the results are presented as hysteresis loops. It is observed that a significant looseness appears after a number of cycles. An alternative to the testing protocol in [7] is proposed.
- Prabha et al. [37]. In the present study eighteen double cantilever monotonic sagging tests were conducted on a commercially available pallet rack connection by varying the most influencing parameters such as column thickness, and connector (end-plate) and beam depth. Analytical models for pallet rack connection are proposed from the results of the experiments.
- Roure et al. [38]. This document compares tests of cantilever boltless (clip-on type) beam-to-column connections performed according to European and American regulations. Significant differences are observed.
- Zhao et al. [39]. This paper refers to monotonic downward (hogging) experiments of beam-to-upright speed-lock connections. The influence of the beam geometrical sectional parameters is analyzed. The tests are conducted according to the European regulation [7] and the American document [9].
- Yin et al. [40]. This work describes monotonic and cyclic experiments on speed-lock beam-to-upright connections; both bolted and bolt-less connections are tested. It is concluded that the bolts improve the connection performance, although they certainly impair its speed-lock character. Two weld beads geometric configurations between the beam and the end-plate are considered: the first, along both lateral sides of the beam; the second, along its whole perimeter (all around). The experiments are performed according to European [7] and American regulations [41].
- Castiglioni [4]. This book discusses the Seismic Behavior of Steel Storage Pallet Racking Systems deeply. Within this context, monotonic and cyclic bending tests on beam-to-upright connections are presented. As discussed in Section 4.3, the cyclic experiments are carried out according to an innovative imposed displacement protocol that differs from [27] in the sense that the effect of the weight of the stored products is explicitly considered; both testing procedures are compared in [29,30,42].
- Giordano et al. [43]. This study reports monotonic and cyclic tests on beam-end connectors of cold-formed steel storage pallet racks. Similar to Yin et al. [40], two weld configurations between the beam and the end-plate are considered: lateral sides and all around.
- Dai et al. [44]. This article presents cyclic cantilever tests of bolted beam-to-upright connections; the tested specimens differ

in the upright thickness, the beam height, and the number of tabs and bolts. The influence of these parameters is discussed, and comparisons with boltless connections are performed; also, the authors propose using the so-called Pinching4 model in OpenSees.

- Gusella et al. [45]. This paper compares monotonic and cyclic tests on both bolted and boltless beam-to-column joints of industrial pallet racks. The tested joints differ in the type of beam-connector (with different welding layouts), the number of tabs, and the relative thickness of the upright and the beam-end connector; the key role of welding in the failure mode is remarked. Significant pinching is identified.
- Gusella et al. [46]. This document refers to an experimental and numerical study on pinching in the hysteretic behavior of steel rack joints; a numerical model considering the stiffness degradation is proposed. It is concluded that the role of pinching is relevant.
- Dumbrava and Cerbu [47]. Beam-connector-upright assemblies are prepared by combining three types of beams (different box cross-section sizes), three types of uprights (different section wall thickness), and two types of connectors (four-tab and five-tab); monotonic hogging tests were performed on 101 assemblies. The influence of these parameters on the connection stiffness is discussed.
- Bové et al. [29,30]. This study covers seismic cantilever monotonic and cyclic tests of speed-lock (boltless) beam-to-upright connections of adjustable pallet rack systems (Figs. 15 and 16). The objective is to propose a new strengthened design of the weld bead's geometric configuration, as the failure does not arise in the weld but in the hooked assembly. This shift is expected to increase the connection ductility; in most of the tests, the new weld design leads to more ductile failure modes.

This section shows that extensive seismic testing on beam-to-upright connections has been conducted worldwide, probably mainly because of the aforementioned relevance of such components in the seismic performance of racks. Apparently, most of the experiments are more oriented to characterize the structural behavior of these connections than to reproduce their actual conditions during seismic excitation.

6. Tests performed on floor connections

Section 4.4 describes the code prescriptions and recommendations on seismic testing of base connections; this section contains actual experiments. In both directions, tests are commonly performed on individual base-to-upright connections; next two paragraphs deal with the down-aisle and cross-aisle directions, respectively.

The monotonic bending behavior in the down-aisle direction is well known. In this sense, the article [48] analyzes and makes relevant remarks on the test mock-up intended to characterize the baseplate (Fig. 7); the results are included in the European code for racks static design [7]. Moreover, the paper [49] also studies the behavior of base-to-upright connections in the down-aisle direction; in that paper, a row of experiments is performed to determine the influence of the baseplate thickness, anchor bolt size, bracket thickness and upright thickness on the connection behavior. These experimental observations reveal that the baseplate eccentric anchor bolt assembly plays a dominant role in the flexural behavior of the connection. Additionally, a component-based analytical model is established to predict its behavior at the initial linear elastic and the nonlinear plastic ranges. The results of this numerical model show a close concordance with the experiments. A general remark of these monotonic experiments in the down-aisle direction is that these connections stiffness and ultimate capacity depend on the vertical compressive forces.

In the cross-aisle direction, the monotonic behavior is less known; for instance, the codes [7,10] do not indicate how to obtain the rotational stiffness. Nonetheless, SEISRACKS 2 suggests that this rigidity is considerable, leading to a stiffer behavior of the shear motion of the upright frame, as described by Fig. 18.a.

Much fewer studies and recommendations can be found regarding cyclic behavior. Concerning this issue, Castiglioni [4] reports an experimental campaign consisting of several cyclic bending tests on base connections for both cross-aisle and down-aisle directions. These tests are performed under bending in two directions (cross-aisle and down-aisle), for several upright compression values. Fig. 19.a and .b display the results of two of these tests for the down-aisle and cross-aisle directions, respectively.

Fig. 19 shows that these connections absorb a significant amount of energy; contrarily to beam-to-upright connections, there is little pinching. However, the energy absorption capacity of the baseplate diminishes as the upright compression increases. It is also noticeable that the tests performed in the cross-aisle direction induce a distortional behavior of the upright. Later, in SEISRACKS 2, the cyclic tests for the cross-aisle direction are improved by combining compressions and bending moments (as described in Section 4.4, see Fig. 8.b). These experiments show that, sliding in the bolted baseplate-upright connections may exist when uncompressing; therefore, the obtained stiffness might not be applicable for design, as the two connectors of the frame act simultaneously (Fig. 18). In this sense, it is proposed to test both base-to-upright connections joined by a ridged cross frame.

Petrone et al. [51] studied the cyclic cross-aisle behavior of floor connections. These tests do not involve bending but study uplift (Fig. 18.b); this is more feasible for racks with only their top levels loaded. The experiments indicate that the inelastic deformation in the baseplate provides a stable hysteretic response with significant ductility and energy dissipation capacity. Finite Element simulations are performed; they help to understand the stress distribution and are used to derive backbone curves. It is concluded that current design methodologies may be unsafe as they do not consider strain hardening nor the membrane effects action in the baseplate; a new approach that accounts for these issues is proposed. Moreover, Tang et al. [52] study through pullout testing (Section 4.8) an inexpensive solution for increasing the resilience of pallet racks in the down-aisle direction. Three solutions are compared: two existing (Fig. 20.a and .b) and an innovative one (Fig. 20.c); they differ mainly in their tension behavior (uplift, Fig. 18.b). The novel solution absorbs more energy than the two other and diminishes the horizontal force. Also, the work [53,54] experimentally demonstrates the benefits of a novel baseplate (Fig. 20.d) in terms of ductility. In this case, the ductility is obtained from localized yielding.

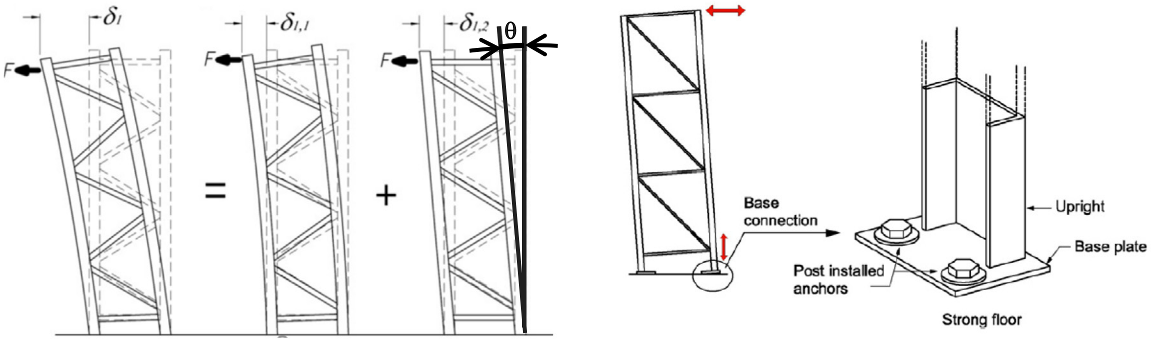
Finally, it is remarked that the bending cyclic testing protocol and mock-up of base connections are analyzed and well defined in SEISRACKS 1 and 2 [3,4,14]; the results of this study for the down-aisle direction are included in the European regulation [10]. No regulation states how to test base connections in the cross-aisle direction. Therefore, the future lines of research should be aligned with this need and define clear and sound protocols.

7. Tests performed on full racks

Experiments on full racks are necessary to understand their global inelastic response, particularly the dynamic one. They are used jointly with tests on individual elements and subassemblies to calibrate numerical models. Several types of tests on full racks are discussed next.

7.1. Static (pushover) tests

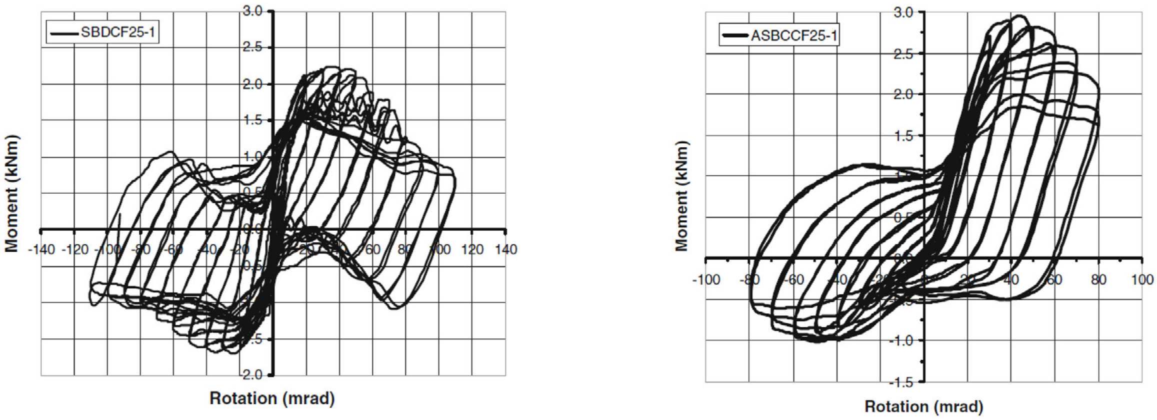
As discussed in Section 4.6, pushover experiments basically consist in pushing the tested rack until collapse (see Fig. 11). The work [3] deeply analyzes the results of several pushover tests; they are part of the European Project SEISRACKS 2. These studies are used for: (i) calibration of numerical models, (ii) initial estimation of the behavior



(a) Total deformation equals the sum of bending plus shear [50]

(b) Uplift of the upright frame [51]

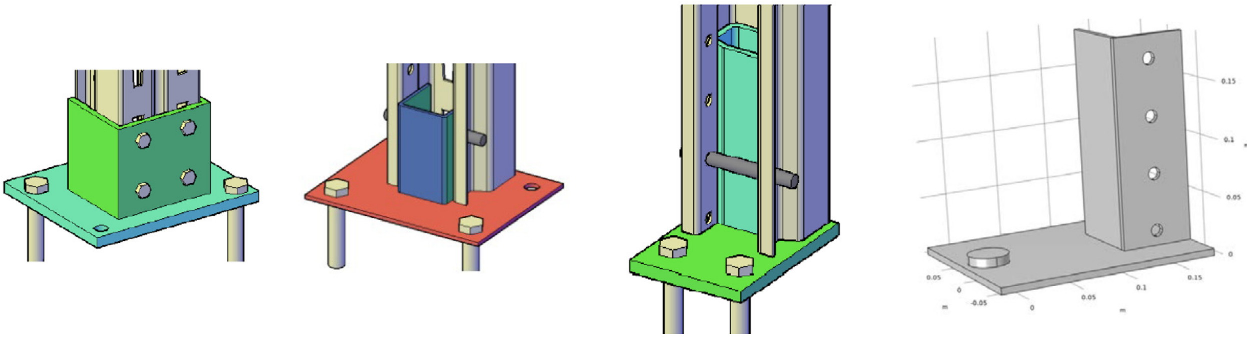
Fig. 18. Cross-aisle frame lateral behavior. (see [50]).



(a) Down-aisle

(b) Cross-aisle

Fig. 19. Baseplate cyclic tests results [4].



(a) Rigid connection [52]

(b) Yielding baseplate [52]

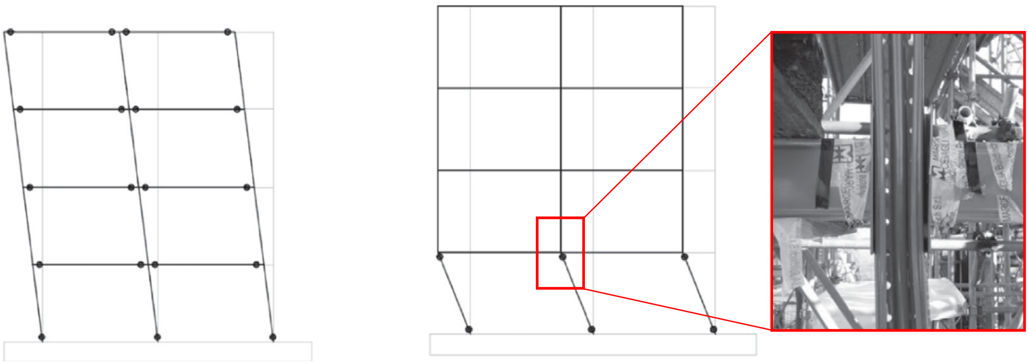
(c) Friction baseplate [52]

(d) Ductile baseplate [53,54]

Fig. 20. Different solutions for base connections for dissipative design.

factor *q* and, (iii) preliminary estimation of the parameters that most influence the racks ductility. Similarly, [55–57] also analyze the results of pushover tests on full racks. The latter refers to hand-loaded shelving racks, which present several differences with respect to conventional racks; the paper states that the design of shelving racks needs to be improved, since current approaches are not reliable. The paper [58] also deals with pushover tests; nonetheless, in this case the pallet racks are not new. The vertical loading is imposed by filling tanks with water with an automated hydraulic network allowing different loading patterns. Finally, the paper [59] also performs pushover tests on racks; gravity is simulated with a sophisticated load system.

Two types of failure are principally observed: (i) a global collapse mechanism, in which all connections fail, thus contributing to the loss of lateral capacity (Fig. 21.a), and (ii) an early soft-story collapse mechanism, ordinarily in the first level (Fig. 21.b). This failure is more brittle (less energy is dissipated), and is mainly contributed by the distortion of the upright cross-sections (zoom view in Fig. 21.b); this issue is similar to the "strong column–weak beam" concept. A global



(a) Global collapse mechanism

(b) Soft story collapse mechanism/ zoom-in of the failure onset of the upright (rear view)

Fig. 21. Types of failure on full racks in pushover tests [Kanyilmaz et al. 2016].

failure mechanism must be pursued for proper dissipative behavior. Two general strategies are proposed for this purpose: (i) stiffening the upright cross-section at the critical points, and (ii) stiffening the base connections to reduce the bending moments at the critical upright sections.

7.2. Dynamic (shaking table and pullout) tests

The actual seismic behavior of racks is intrinsically dynamic. Static tests (either on the full structure, components or subassemblies) are useful to determine stiffness parameters (force–displacement relationship, including ductility). However, they cannot capture inherent dynamic issues, such as damping, inertial effects and fatigue. In this sense, dynamic tests constitute a much more convenient option. Obviously, the most reliable conclusions can be derived under conditions closer to reality; therefore, the observation of collapse mechanisms for real racks provides useful information. The work [60] classifies these failure modes into three categories (Fig. 22): (i) down-aisle mechanism (Fig. 22.a) after the progressive or abrupt failure of beam-to-upright and floor connections, (ii) failure of the floor connections in the cross-aisle direction (Fig. 22.b), and (iii) progressive collapse of the whole facility (Fig. 22.c).

The racks in Fig. 22 are not brand new, perhaps significantly predamaged due to their daily use. In this sense, paper [61] warns about the importance of proper maintenance to diminish the risk of seismic damage. On the other hand, the rack loading patterns can be highly variable. These issues can influence their seismic behavior; therefore, even though dynamic tests are the most reliable option, important uncertainties might still hold.

Dynamic tests are difficult (if not impossible) to be conducted on individual components and subassemblies and must be performed on full racks. As discussed in Section 4, two major types of dynamic experiments have been proposed: pullout (the structure is laterally pulled and released in order to analyze its natural response, Section 4.8) and shaking table (the structure is attached to a platform driven by sine sweeps or recorded earthquake acceleration signals, Section 4.9). Pullout tests serve primarily for system identification, while shaking table tests serves for system identification and to reproduce the behavior under seismic excitations. Such tests are described in Fig. 23.b and .a, respectively.

Krawinkler et al. [31] and Chen et al. [62] describe an extensive campaign of tests on subassemblies and full racks; these studies include shaking table testing and pullout experiments and serve as a starting point for further researchers. From these studies, Castiglioni et al. [63] present shaking table experiments on four full-scale pallet racks with the aim of standardizing their seismic design. The structures were submitted to the following dynamic tests: (i) variable frequency sine sweep to obtain the first vibrational modes, (ii) single impulses to evaluate the damping and (iii) artificial earthquake, generated according to EN 1998 [12], fitting the acceleration spectrum for soil type D. Pallet sliding was observed in all the tests, even for very low ground acceleration. Also, Jacobsen and Tremblay [64] analyzes the results of pull-back and seismic shaking table tests on adjustable pallet racks. Pallet rack sliding was observed during the dynamic tests. Additionally, the hysteretic behavior of both beam-to-upright connections and base plates is measured. Finally, a numerical model for the rack response is proposed, including pallet sliding (OpenSees). The model is used to study the seismic response of six bay racks with 3–6 levels. Moreover, Maguire et al. [65] and Maguire et al. [66] show the results of diverse cross-aisle shaking table tests on full racks. This investigation compares the effect of using different baseplates; the merchandise sliding is restrained since it is out of scope. The results show that failure is mainly due to overturning (Fig. 24.a). Fig. 24.b and .c contain images of damaged baseplates.

The work [66] concludes that allowing uplift of the baseplates provides better performance for overturning; this remark agrees with the discussion in Section 6.

Additionally, Jayachandran [67] performs shaking table tests on a two-level single-bay pallet rack. The structure is excited with a variable frequency sine sweep, aiming to obtain the vibration modes, and also undergoes the excitation of an actual seismic input signal (El Centro, 1940). The results of the experiments serve to calibrate the numerical model used for larger racks simulation. Moreover, the paper [53,54] aims to demonstrate the advantages of a novel base isolation system. With this objective, shaking table experiments are performed on both isolated and fixed-base racks. Firstly, uniaxial cross-aisle real-time tests are performed; important reductions in the absolute accelerations of the stored goods are observed. Additionally, numerical simulations are carried out to corroborate the observations. Finally, the article [60] discusses the results of shaking table experiments on adjustable pallet racks; as in the previous studies, damping is identified through sine sweep and pullout experiments. Next, shaking table experiments are conducted to capture their inelastic behavior. It is concluded that ordinary racks are able to endure large inelastic deformations without loss of stability.

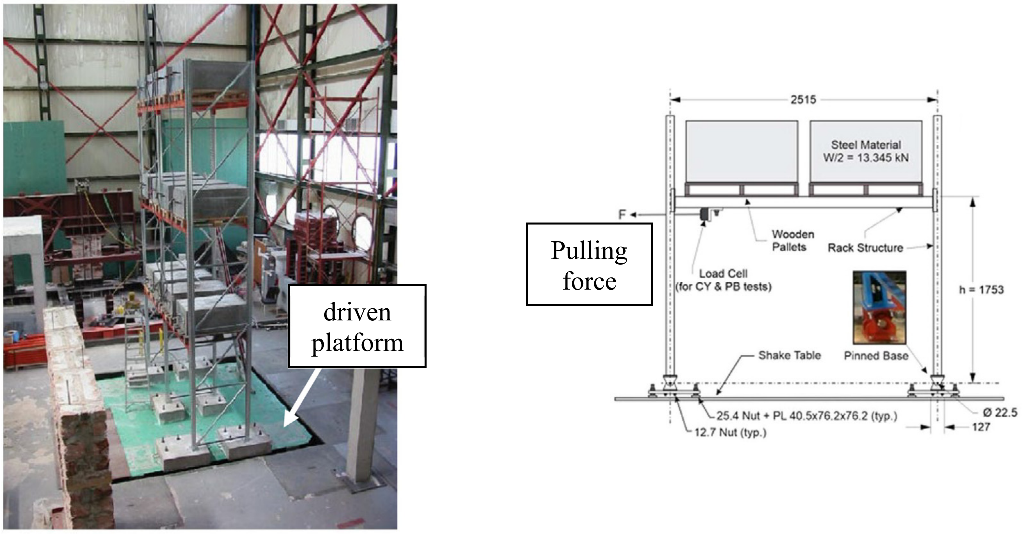
As a general remark, shaking table tests are generally preferred over other dynamic experiments; the main limitation is their high cost and complexity. They can be used to analyze the racks nonlinear time-history response (including sliding of the stored goods); moreover, they are a must to point out the benefits of any dissipative or isolating system [68]. Nonetheless, despite these advantages of shaking table tests, there is a scarcity of recommendations in the design codes.

(a) Down-aisle mechanism

(b) Baseplate damaged in the cross-aisle direction

(c) Progressive collapse of the whole facility

Fig. 22. Typical failures in actual facilities after earthquake [60].



(a) Shaking table test [4]

(b) Pullout test [63]

Fig. 23. Dynamic tests on full racks.

8. Pallet sliding tests performed

Products stored on pallet racks are not attached to the structure, but merely placed on it. Therefore, sliding is likely to occur, leading to energy dissipation but also to possible falling/shedding of pallets. Obviously, the former effect is beneficial, while the latter is not. Recent research on pallet sliding has been done. In this sense, some numerical studies serve as a starting point; nonetheless, this phenomenon is rather complex and cannot be analyzed only numerically. The next paragraph discusses the reported tests.


(a) Frame overturning (b) Base plate the failure (c) Failure of concrete

Fig. 24. Shaking table tests results. Typical failures in the cross-aisle direction [66].


(a) Inclined plane device (static) [3] (b) Shaking table (dynamic) [69]

Fig. 25. Setups of experiments for characterizing the sliding.

The paper [69] has two major objectives: to characterize the sliding behavior of palletized goods, and highlight the benefit of incorporating slightly inclined shelving; both are reached through shaking table tests. Complementarily, the European projects SEISRACKS and SEISRACKS 2 intend to estimate the static friction coefficient between structure and pallets (Section 4.11). As part of these projects, Castiglioni et al. [3] and Castiglioni et al. [70], describe static experiments conducted on an inclined plane (Fig. 25.a).

The experiments in Fig. 25 are performed in the cross and down-aisle directions. The eccentricity of the merchandise center of mass in the down-aisle direction shows little influence on the sliding onset. Works [70,71] study the sliding of pallets over the beams in the cross and down-aisle directions; the results of several shaking table tests on very low (short) structures for different materials and surface finishes have been analyzed (Fig. 25.b). The results show that the dynamic bending of the beams (in both directions) affects the pallet sliding, favoring earlier slippage (i.e., for low accelerations).

9. Concluding remarks

This paper presents a state-of-the-art review on seismic-oriented experiments on adjustable pallet rack systems. Four major types of tests are considered: on particular critical components of racks (connections between beams and uprights, braces and uprights, and floor and uprights), on subassemblies (including mainly beam-to-upright connections), on full racks (pushover, pseudo-dynamic, pullout and shaking table) and on the stored goods (sliding and tilting).

The performed review provides the following major remarks:

- **Regulations**. The major design codes for racks (European and American) provide, in general, insufficient guidelines for most of the regulated seismic experiments; even several important tests (e.g., pushover, and shaking table tests, among others) are not standardized. Some of the standardized tests (as those on beam-to-upright connections) are quite similar to the non-seismic experiments, and might not reproduce the seismic behavior with sufficient correctness; the research projects SEISRACKS (1 and 2) proposed modifications of these tests, but the regulations still do not consider them. On the other hand, the European seismic design code proposes a loading protocol (for beam- to-upright cycling testing) which is not totally feasible, and is rarely implemented. Finally, most of the code tests on components are oriented to validating existing elements; conversely, promoting innovation is also highly necessary.
- **Beam-to-upright connections**. These connections are a major source of ductility; hence, their tests are of major interest. Extensive testing has been carried out worldwide; the most important remark is that significant energy dissipation capacity is observed.

However, this capacity might not be sufficient to absorb the input seismic energy without unacceptable damage. Moreover, results exhibit high scattering and are little reliable; finally, significant pinching is observed. Therefore, more testing on innovative ductile elements (with superior energy dissipation performance) is necessary. Currently, these considerations prevent the design from being based on the dissipative approach.

- **Base connections**. These connections also are a major source of ductility; conversely, the tests performed can be considered too scarce. Hence, concluding remarks are only preliminary.
- **Tests of full racks**. Non-destructive tests (pullout) and destructive tests (pushover, pseudo-dynamic and shaking table) have been proposed. Pushover tests are the least expensive, being inherently static and, thus, not useful to estimate dynamic parameters; however, ductility is commonly inferred. Pseudo-dynamic tests provide a closer insight into the dynamic issues, although sliding and damping cannot be straightforwardly estimated. Shaking table experiments are the costliest, reproducing the actual dynamic behavior quite closely, and providing reliable information, even on sliding and damping.
- **Seismic isolation**. Little research effort has been devoted to advanced seismic protection technologies (base isolation and energy dissipators), although they might prove high efficiency.

CRediT authorship contribution statement

Francisco López-Almansa: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Oriol Bové:** Writing – original draft, Methodology, Investigation, Conceptualization. **Miquel Casafont:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Miquel Ferrer:** Writing – review & editing. **Jordi Bonada:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francisco Lopez Almansa reports financial support was provided by Ministry of Science Technology and Innovations.

Data availability

Data will be made available on request.

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