Full-scale tests of industrial steel storage pallet racks

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ABSTRACT: Industrial steel storage pallet racks are framed structures typically made of cold-formed steel profiles. The characteristics and the variability of the racking systems in terms of components and configurations make their behaviour quite complex to be predicted and the "design by testing" approach is commonly adopted. As part of an extensive research on the racks' static and seismic behaviour carried out at the University of Trento, a total of eight full-scale tests on four-level two-bay commercial pallet racks were performed, taking advantage of an innovative full-scale testing set-up. The experimental plan comprised of two preliminary tests in which racks with an initial out-of-plumb were vertically loaded up to their collapse and of six monotonic push-over tests with three different levels of vertical loads and an inverse triangular pattern of horizontal forces in the down-aisle (longitudinal) direction. Tests' results enabled investigation of the failure modes and evaluation of the racks' behaviour factor *q*. The main features and findings of this experimental study are presented and discussed in the paper.

KEYWORDS: steel storage racks; cold-formed steel; experimental analyses; full-scale tests; push-over tests

1 INTRODUCTION

Industrial steel storage pallet racks are nowadays worldwide used in the logistic field to store goods and products. These structures are prefabricated framed light systems typically made of cold-formed steel profiles. The main structural components are the uprights, often made of open mono-symmetric perforated profiles and the beams which can have both an open or a boxed section. Uprights are connected at the base to the concrete floor and, at different levels, to the beams. Both joint's types, i.e. base-plate and beam-to-upright joints, are non-linear semi-rigid joints characterised by a non-symmetric response (Dubina et al. (2012)). Racking systems are usually braced in the cross-aisle (transversal) direction only. As a consequence, their lateral stability is provided by the sole degree of continuity offered by the base-plate and beam-to-column joints. Therefore, racks design calls for balancing a great variability of global and local parameters in terms of configuration, local behavioural features, such as the performance of open mono-symmetric perforated members, prone to relevant buckling phenomena, global frame sensitivity to the second order effects, and response of non-linear semi-rigid joints. A quite complex behaviour to be predicted theoretically or numerically. Therefore, the so-called "design by testing" approach is commonly adopted in racks' design (Baldassino and Zandonini (2011)). This method, recommended also by the main design racks standards (EN15512 (2020), EN16681 (2016), AS4084 (2012), ANSI MH16.1 (2021)), makes use of the results of tests on structural components and sub-assemblies in association with the design rules typical of the traditional steel structures' design. As a consequence, a number of experimental studies on racks' components and sub-assemblies can be found in literature. In addition, various experimental investigations focused on the overall frame structural performance aiming at getting an insight into the racks' global response and at defining specific design rules for these structures.

Although numerous experimental investigations have been carried out, the variability of the testing set-ups, of the loading procedures, of the frame configurations and of the characteristics of the specimens adopted in the different researches, makes difficult a direct comparison of the studies outcomes and calls for additional work.

Extensive research has been recently completed at the University of Trento, focusing on the static and seismic performance of the racks at both the components and the global levels (Bernardi (2021)). A reference racking system was selected as a case study and experimental and numerical analyses were carried out on uprights, beam-to-column and base-plate joints, as well as on full-scale racks. In detail, to investigate the racks' global response, a total of eight full-scale tests on three-level two-bay commercial pallet racks were accomplished, using an innovative full-scale testing set-up, which allows applying both vertical and horizontal loads, up to the collapse (Gelmini and di Gioia (2017), Baldassino et al. (2021)). The experimental study comprised of two preliminary tests, in which specimens with an initial out-of-plumb were tested by applying vertical loads up to the collapse, and six monotonic push-over tests. The latter tests were performed with three different levels of vertical loads, selected on the basis of the two vertical loads tests' results. An inverse triangular pattern of horizontal forces in the down-aisle (longitudinal) direction was then applied up to the specimen's collapse. The tests provided an insight into the failure modes and the global response of racks, investigated by varying the applied gravity loads. In addition, push-over tests allowed evaluating the behaviour factor q of the analysed rack' configurations. In this paper the main features and results of the study are presented and discussed.

2 STATE OF THE ART

A number of experimental studies were carried out on the racks' seismic response in the mid-1970s – early 1980s at the John A. Blume Earthquake Engineering Center (Krawinkler et al. (1979), Chen et al. (1980)), which allowed identifying the key role played by the base-plate and beam-to-column joints and by the upright frames on the racks global response. In particular, the significant influence of the P-Δ effects on racks' lateral behaviour was pointed out. Krawinkler et al. (1979) carried out forced vibration, quasi-static monotonic and cyclic full-scale tests; Chen et al. (1980) performed full-scale static-cycle tests on two typologies of racks and conducted cantilever and portal tests on a number of rack subassemblies. The effects of different types of goods were also investigated by means of shake-table tests performed on a full-scale rack.

After a period when a limited number of researches were performed, in the last twenty years the seismic performance of racking systems has gained new attention in the research community. Full-scale tests on different types of racks were carried out by different research groups (Castiglioni et al. (2003), Filiatrault et al. (2008), Freitas et al. (2010)). Castiglioni et al. (2003), within the ECOLEADER research programme, investigated the influence of the bracing system geometry and identified the sliding of the pallets on the beams as a serviceability limit state. Filiatrault et al. (2008) conducted uniaxial and triaxial shake-table tests on pallet racks with different base-plate joints, to evaluate the contribution of the base isolation to the racks' behaviour. The authors demonstrated that the base isolation system enhances the structures response, extensively reducing both the accelerations and the inter-storey drifts in the cross-aisle direction and the accelerations in the down-aisle direction, if compared with the response of a rack with the same characteristics but anchored at the base. Freitas et al. (2010) studied the performance of drive-in racks revealing the role played by the connections in ensuring the racks global stability. In addition, the importance of a proper appraisal of the base-plate joints semi-rigidity was identified for the characterisation of the system response.

The performance of drive-in racking systems subjected to impacts and under different horizontal loading conditions were explored (Gilbert and Rasmussen (2011, 2012), Ahmed et al. (2016) and Shaheen and Rasmussen (2019)). In detail, Gilbert and Rasmussen (2011) found out that the following parameters affect the most the progressive collapse of the drive-in racks subjected to impact: the height of the impact force and of the rack, the type of the rack (designed for light or heavy loads), the number of pallets loading the rack and the friction between the pallets and the rail beams. Moreover, Gilbert and Rasmussen (2012) showed that the presence of the pallets increases the stiffness of the racks. As to drive-in racks, Ahmed et al. (2016) studied their down-aisle seismic behaviour, while Shaheen and Rasmussen (2019) investigated the cross-aisle direction response by means of full-scale shake-table tests on racks characterised by different bracing systems, resulting in structures with different stiffness, damage location and lateral sway.

Recently, within the SEISRACKS2 project, Castiglioni et al. (2014) performed full-scale push-over tests on braced and un-braced pallet racks and calculated the behaviour factor of these structures (*q*) with the aim of evaluating their global ductility. On the basis of their findings, Kanyilmaz et al. (2016a) and Kanyilmaz et al. (2016b) recommended a value of the behaviour factor *q* to be adopted in design equal to *1.5* or *2.0* for unbraced racks, on the basis of the expected collapse behaviour, and higher than *2.0* for braced structures with ductile behavior. In any case, the authors identified the need of guaranteeing sufficient over-strength to the base connections and to the bracing connections to prevent brittle collapse in unbraced racks and in braced structures, respectively. Jacobsen and Tremblay (2017) fulfilled an experimental programme consisting of quasi-static cyclic, pull-back and seismic shake-table tests on one-level one-bay rack specimens and, more recently, Firouzianhaji et al. (2021) executed full-scale shake-table tests on two-bay and two-level rack frames, i) confirming the importance of the beam-to upright connections stiffness on the racks global response and ii) finding that the racks designed according to the New Zealand standard were able to sustain large inelastic deformations without loss of stability.

3 THE TESTING SET-UP

The tests here presented were performed using an innovative testing set-up designed and built by the Research and Development Division of Metalsistem S.p.A., with the contribution of the University of Trento and of the Politecnico di Milano (Gelmini and di Gioia (2017), Baldassino et al. (2021) and Baldassino et al. (2022)).

The main 'component' of such a testing set-up is the 'rigid' steel trussed testing tower, depicted in Figure 1, which acts as reaction frame. It has a height of *24.5m* and plane dimensions of *12.35m × 12.35m* and allows testing structural systems with a maximum height of *24.5m*. The testing tower is equipped with independent dynamic actuators which allow applying different vertical forces on each bay of the specimen, as well as different horizontal loads at each storey level (Figure 2). In the following, the set-up adopted to test a four-level two-bay rack is described, although different configurations could be tested.

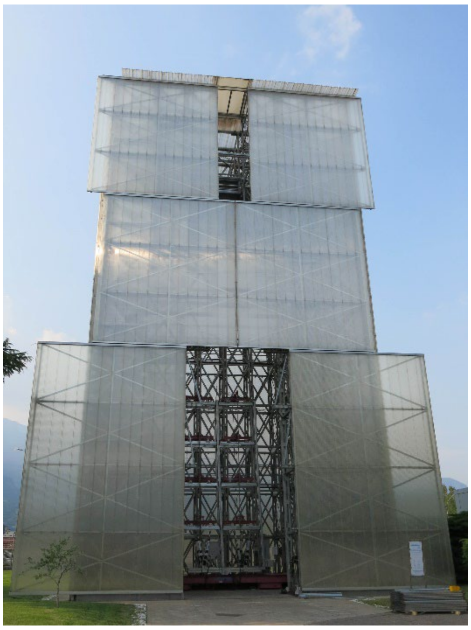

Figure 1. The testing tower and a specimen built-in.

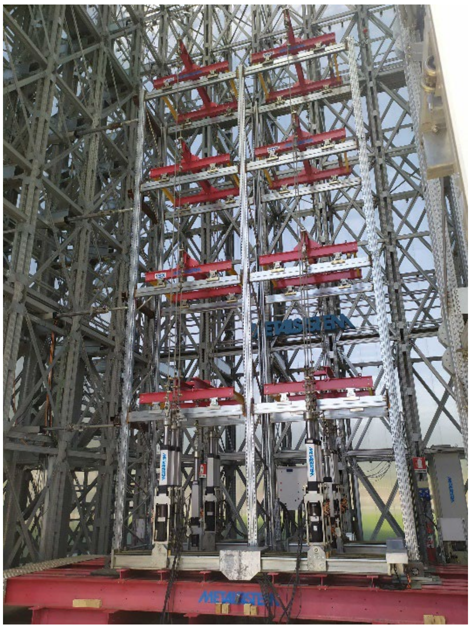

Figure 2. Specimen in the testing rig, with four horizontal actuators and fourteen vertical actuators.

The vertical loads are applied to the tested structure using fourteen dynamic actuators. This system was preferred to the 'popular' use of dead loads realised by tanks filled with water or concrete blocks (Castiglioni et al. (2014)), in order to get safer collapses and to appraise the structural response beyond the collapse. The key point of this testing set-up is its capability to maintain the verticality of the loads during all the phases of the tests, even when the specimen sways significantly. This is possible because the vertical actuators can horizontally translate on rail beams (Figure 3), placed on a steel grid fixed to the concrete foundation of the testing tower.

Figure 3. View of the vertical loading equipment mounted on the rails and of the loads transfer system.

The movement of the actuators at each level is imparted by motorized sliders and is controlled on the basis of the horizontal displacement of the rack measured at the corresponding level. As shown in Figure 2, for the case of a four-level rack, a couple of actuators applies the vertical load at each level and for each bay, except for the first level, for which one actuator is employed for each bay. The load is transmitted by the actuators on each pallet beam by means of a counter-beam system, which is pin-connected to each pallet beam at its quarters. The counter-beams systems are adopted to avoid local buckling phenomena of the rack's beams.

The horizontal forces are applied using four independent actuators located at the rack's levels. Each actuator can follow a different load application protocol, to simulate different loading patterns. To avoid the local crushing of the uprights, the actuators are connected to a beam distributing the load to the specimen (Figure 4).

Figure 4. View of the horizontal load transfer system.

All the actuators, with a maximum capacity of *50kN* each, are coupled with load cells to continuously measure the loads applied during the tests. To measure the horizontal displacement of the rack at each level, two wire transducers with a measuring range of *5000mm* are used. They were fixed to an independent structure with respect to the tower. Both loads and displacements are measured with a frequency of *2Hz*.

4 THE REFERENCE STRUCTURE

A typical steel pallet rack was selected as case study for the research. The structure is a commercial rack made of cold-formed steel profiles. Figure 5 shows the main components of the rack. The uprights have an open mono-symmetric cross-section, a nominal thickness of *1.45mm* and are provided with regular patterns of perforations along their length. The beams are stiffened box sections, obtained by bending a coil with a thickness of *1.45mm*. The beams are welded at the ends to a bracket with a thickness of *2.8mm*, which is mechanically connected to the uprights by five tabs, hooked into the upright perforations. The connection is also provided with a safety pin, to avoid the accidental unhook of the beams from the uprights. The base-plate joints consist of a non-symmetric cold-formed steel base-plate (with a thickness of 4mm) connected to the upright by eight bolts M8 class 8.8 and to the floor by four mechanical fasteners M16 type Hilti HSA. The nominal grade of the steel used for the components is S350GD, except for the brackets which are made of steel grade S355MC. For the sake of confidentiality, required by the industrial manufacturer, the geometrical and mechanical properties of the rack's component are not explicitly reported. For the same reason the tests' results are presented as non-dimensional data.

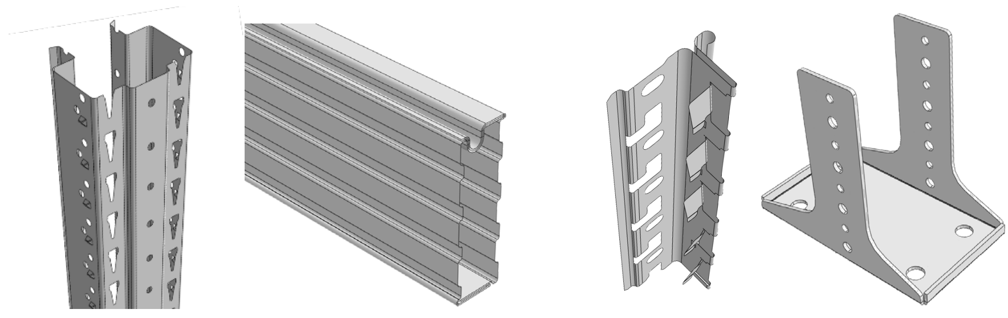

Figure 5. View of the main elements of the racks: upright, beam, bracket and base-plate.

Four-level two-bay racks braced only in the cross-aisle direction with irregular "D" bracings were tested (Figure 6). The structures had a nominal height of *8000mm*, with an inter-storey height of *2000mm*, and the bays were *1927mm* wide. For all the tests the racks were provided with 'ideal' hinges at the bases. In order to approximate this boundary condition, the base-plates of the specimen's uprights were connected to steel plates mounted on a system provided with cylindrical pins and ball bearings. Preliminary checks were then carried out, and confirmed the adequacy of the details adopted. The use of hinges at the base allowed reducing the parameters that could influence the tests results. In any case, the impact of different base restraints on the racks overall response have been numerically investigated through parametric analyses (Bernardi (2021)), that confirmed the remarkable sensitivity of the racks global response to the base restraint: racks modelled with non-linear base connections, simulating the experimental response of the base-plate joints, exhibited an overall response similar to the one of a structure with fixed bases.

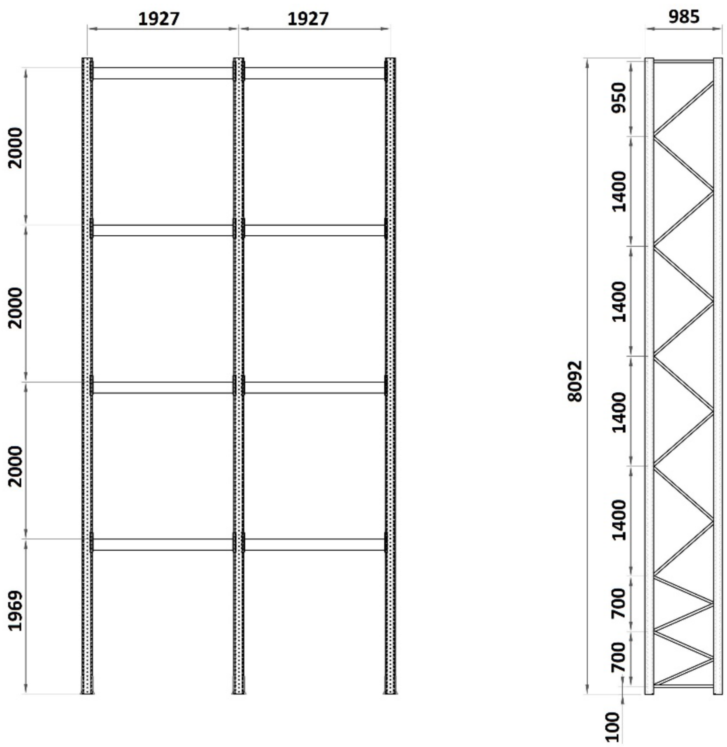

Figure 6. Front and lateral view of the tested racks. Measures in millimeters.

5 THE EXPERIMENTAL PROGRAMME

The experimental programme comprised of eight full-scale quasi-static tests: two tests under vertical loads and six push-over tests in the down-aisle direction. The tests under vertical loads represented the basis for the subsequent push-over tests, as detailed in Section 5.2.

To the best of the authors' knowledge, current design codes (EN15512 (2020), EN16681 (2016), AS4084 (2012), ANSI MH16.1 (2021)), do not require full-scale tests for the design of racks and do not provide any 'ad-hoc' specifications for the testing of full-scale racking systems. However, it is a general view that full-scale tests allow effectively investigating the racking structures complex overall behaviour. The lack of recommendations in the design codes is probably due to the cost and complexity of the testing set-ups and procedure which are required for the tests.

5.1 *The vertical loads tests*

Two tests on two nominally equal specimens were first performed monotonically increasing the vertical loads applied to the racks up to their collapse. In tests, the same vertical loads were applied at each level. The structures had an applied initial out-of-plumb in down-aisle direction of 1/126, to amplify the influence of the second order effects on the racks' response. The out-of-plumb was achieved by means of plates with predefined thickness under the base of the central and lateral upright frames, to vary their levels. The value of the assigned imperfection is higher than the one typically adopted for the racks design (i.e. 1/200, commonly) and with respect to the standards recommendations for design tolerances (EN 15620 (2008)) i.e. 1/500 or 1/350 for unloaded racks). The cross-aisle imperfections were measured prior to the tests and proved to be equal to 1/545, which is lower than the standards limit (i.e. 1/500 or 1/350).

The tests aimed at evaluating the load bearing capacity of the racks. Figure 7 shows the results in terms of total vertical load vs. drift measured at the top level of the specimens. The loads are normalised with respect to $6 \times A_g \cdot f_y$, where A_g is the gross area of one upright and f_y is the nominal yielding steel strength of the upright. Since each rack has 6 uprights, $6 \times A_g \cdot f_y$ would represent the total sectional load carrying capacity at yield of all the uprights of the rack. The drift is the average of the lateral displacements measured by the two transducers applied at the upper rack level. The scatter of the results is rather limited (Figure 7), with a normalised standard deviation equal to 0.0028. The initial non zero axial load associated with zero drift, that can be observed in Figure 7, is the weight of the system used to connect the loading distribution system to the vertical actuators and to apply the loads.

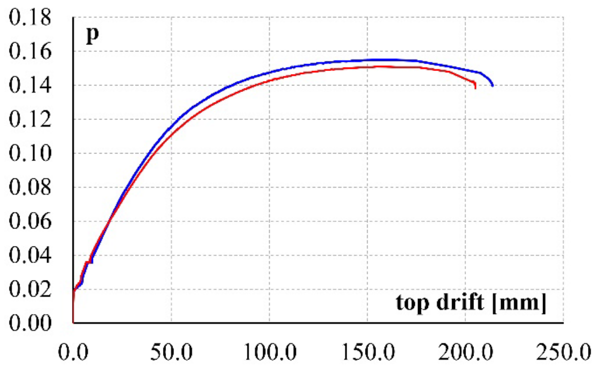

Figure 7. Normalised vertical load vs. top drift for the two vertical loads tests.

Both tested racks collapsed by buckling in the same global sway mode (Figure 8), with plastic deformations of the beam-to-column nodal zones of the first load level. The deformation of the joints was characterised by the local and global deformation of the brackets and by the deformation of the uprights. The ‘hinged’ base-plate joints showed no deformations during the tests.

Figure 8. Collapse of a full-scale rack subjected to vertical loads with an initial out-of-plumb of 1/126.

Aiming at appreciating the overall deformation of the specimens during the tests, Figure 9 provides the evolution of the lateral drift of one of the rack frames with the increase of the percentage of the collapse load P_{max}. The total drifts at each level of the structure are reported for one of the tested specimens, being very close to each other. In the figure, it is apparent the increase of the rack lateral displacements when the ultimate loading condition is approaching.

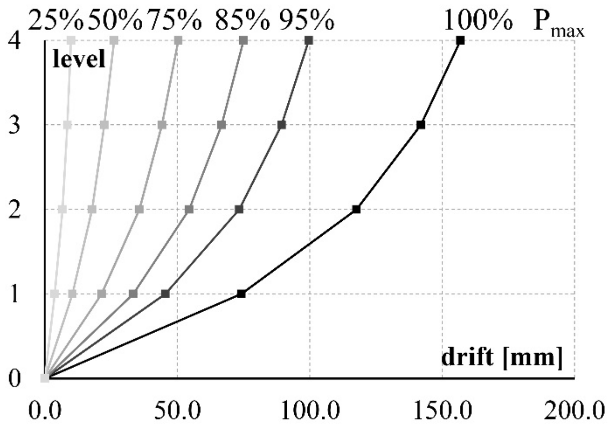

Figure 9. Drifts measured at each level of a rack for different percentage of the collapse load P_{max}.

5.2 *The push-over tests*

Nowadays static push-over analyses are commonly considered by the standards for the seismic design of structures (EN1998-1 (2013)) and racks (EN16681 (2016)). Nevertheless, although the racks design practice is strongly based on the experimental tests, the racks' design codes (EN15512 (2020) and EN16681 (2016)) do not explicitly ask for full-scale tests results to be adopted and no guideline is available neither for the testing nor for the use of tests results, when available.

Push-over tests were carried out in the down-aisle direction, considering three levels of vertical loads and an inverse triangular horizontal loading pattern (EN1998-1 (2013)). Two tests were performed for each level of vertical load *Q*. The loads *Q* were defined as a percentage of an "experimental service load" (*ESL*), calculated by reducing the experimental collapse load obtained by the vertical loading tests (see Section 5.1) for the load factor γ for variable loads, assumed equal to 1.4 (EN15512 (2020)). The tests were performed with vertical loads equal to *ESL*, *2/3ESL* and *1/3ESL*.

The vertical loads were first applied to the racks, without imposed out-of-plumb both in the cross-aisle and the down-aisle directions, and then maintained constant during the horizontal loading, up to the collapse. The horizontal forces were then monotonically applied with an inverse triangular load pattern, to impose a deflected shape representative of the first modal shape of the frame. The triangular load pattern was kept during the tests, using the top horizontal actuator as reference for the force controlled loading protocol. Therefore, the top actuator had a rate of lateral loading increase (0.15kN/min) equal to 4 times that the one of the lower actuator.

The ultimate shear condition was associated with sway frame instability. The global capacity curves of the structures for the three levels of vertical loads are plotted in Figure 10, in which the normalised total base shear *V* vs. top drift curves are reported. The base shear is normalised by the maximum value of base shear obtained in the tests for *Q = 1/3ESL*. Comparing the two tests performed at the same vertical load, the scatter of the results is quite limited, except for the case of *Q = 1/3ESL*, in particular in the plastic range of the curves. No apparent differences neither locally or globally were observed during the experiments. Further tests should hence be necessary to clarify the higher scatter of results, by examining the response in the range of low gravity loads. In any case, Figure 10 enables an appraisal of the influence of the level of gravity load on the racks global response.

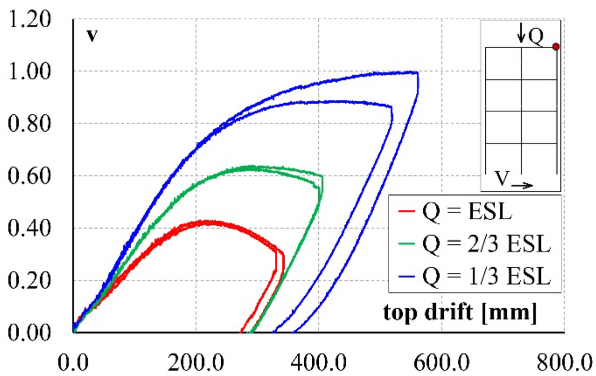

Figure 10. Normalised push-over curves for the six push-over tests, with three levels of vertical loads Q.

The comparison of the curves shows that the initial lateral stiffness of the rack is almost not affected by the level of vertical load *Q*. On the contrary, increasing the lateral displacement, the influence of *Q* is more apparent, in terms of both lateral stiffness and maximum shear load. In detail, reducing the vertical load from *ESL* to *2/3ESL* and *1/3ESL* leads to a mean increase of the maximum top drift at collapse of approximately 19% and 61%, and of the maximum base shear force of approximately 50% and 122%, respectively.

Figure 11 collects the drifts measured at each load level of the racks at collapse for the three levels of gravity loads. The figure permits to compare the global deformation and shows that the specimens can sustain larger deformations when subjected to lower levels of gravity loads.

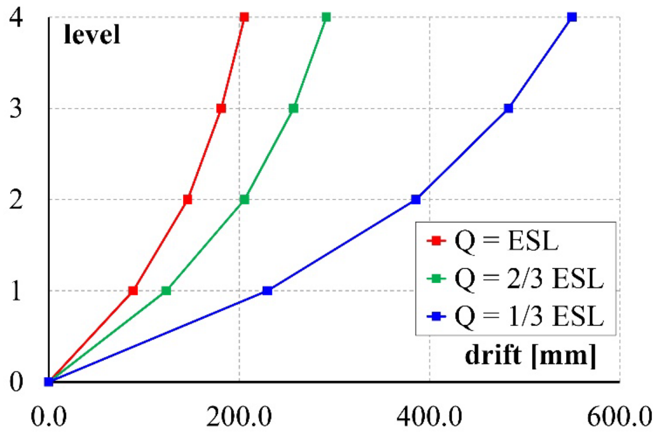

Figure 11. Comparison of the racks' deformation at the collapse load for the three levels of gravity load, in terms of drifts measured at each level of the rack.

The evident higher deformability of the frames in case of lower levels of vertical loads is probably due to the flexibility of the racks, whose behaviour is highly influenced by the degree of continuity offered by the beam-to-column joints and by their peculiar performance, which changes when different levels of gravity loads are applied on the beams (Rosin et al. (2009), Castiglioni et al. (2014) and Asawasongkram et al. (2014)). The key role played by the joints in defining the racks' global response can be appreciated also if the frames' failure mode is considered. Figure 12 highlights the localization of the plastic deformations of the frames at the joints level. This can be associated with the push-over curves reported in Figure 10, which shows the unloading branches of the curves, highlighting the build-up of plastic deformations of the frames in the nodal zones and the limited elastic deformation recovery.

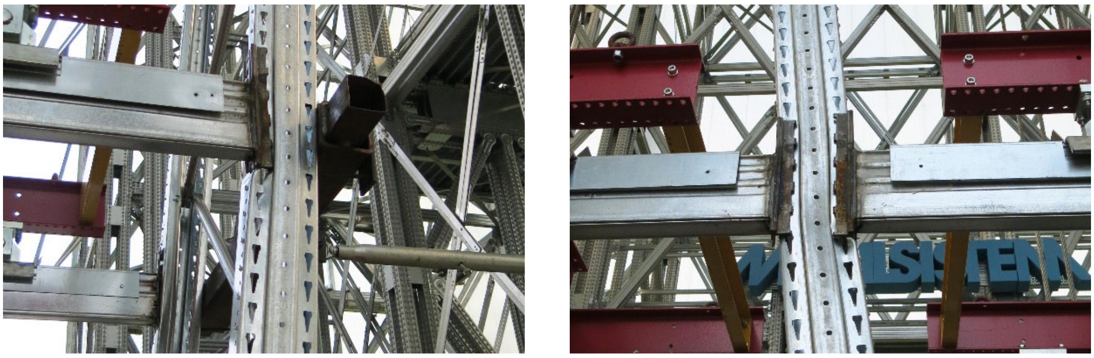

Figure 12. Details of the plastic deformations of the first level joints for a test performed with Q = 1/3 ESL.

All the racks showed the same global collapse mode for lateral sway. The failure mode exhibited by a specimen tested with *Q = 1/3ESL* is depicted in Figure 13, being representative of the typical global behaviour of the tested racks. The structures showed the sway of their first level, with the plastic deformation of the nodal zones of the first load level (Figure 12) and, although less significant, of the second level. The deformations of the joints were the same as the ones observed in the vertical loads tests and also observed in the beam-to-column component tests performed on the same type of joints (Bernardi (2021)).

Figure 13. Collapse of a full-scale rack subjected to push-over loading with Q = 1/3 ESL.

As a general comment, the tested racks, due to the symmetry of the structures themselves and of the loading conditions, showed no global torsional deformations.

To get a better appraisal of the specimen global behavior, Figure 14 shows the lateral displacements of the racks tested with *Q=1/3ESL* at each level of the structure for six steps, defined as percentage of the maximum shear achieved by the specimen at failure. Besides, Figure 15 illustrates, for the same test, the evolution of the inter-storey drifts at three levels of maximum total shear force V_{max}. It is apparent that the inter-storey drifts remarkably decrease with the height, confirming that the most of the total lateral displacement is localized at the first and second level of the rack. The figures are related to one of the couple of tests, being representative of also the other. Although the figures are related to the lowest level of *Q*, the outcomes do not depend on the magnitude of the vertical load.

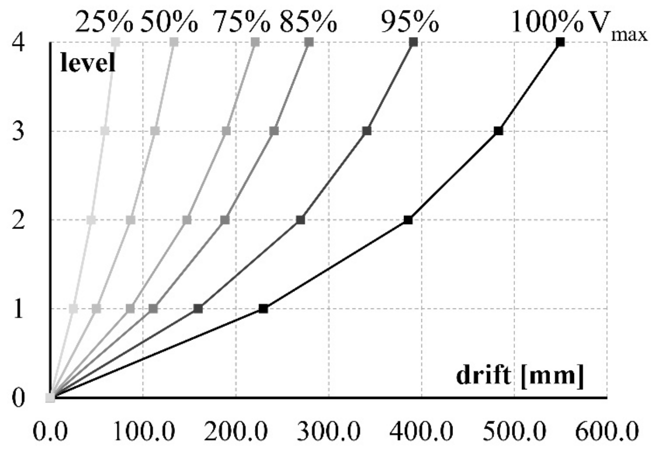

Figure 14. Drifts measured at each level for different percentage of collapse load, for push-over tests with Q=1/3ESL.

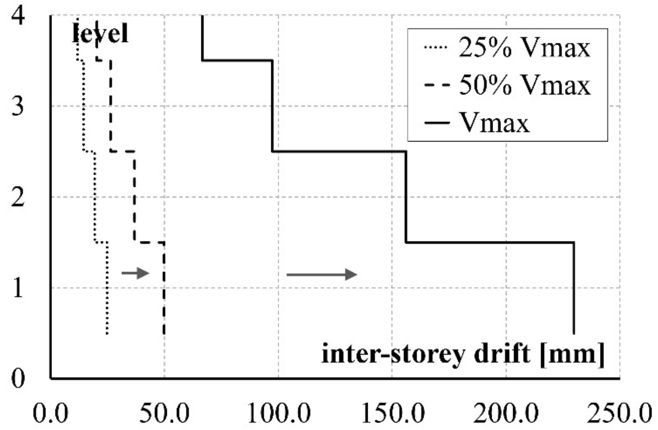

Figure 15. Inter-storey drifts at each level for different percentage of the maximum total shear load, for push-over tests with Q=1/3ESL.

6 THE BEHAVIOUR FACTOR

The push-over tests results also provided the base for the evaluation of the so-called behaviour factor q of the rack frame tested (EN1998-1 (2013)). This factor is used in seismic design process to account in a simplified way for the non-linear behaviour of the structures and their capacity to dissipate energy, by reducing the forces obtained from linear elastic analyses. Low values of behaviour factor ($q \leq 2$, in accordance with EN16681 (2016)) are typical of low dissipative structures. On the contrary, dissipative frames are usually associated with larger values of q ($q > 2$) and therefore reduced values of the design seismic forces can be adopted, this way exploiting the ability of the structure to sustain plastic deformations. The details of the structures should hence be designed in accordance with the design assumption on its dissipative behaviour.

The behaviour factor q is commonly defined as the product of the over-strength Ω and the ductility ratio μ:

$$q = \Omega \cdot \mu \tag{1}$$

with

$$\Omega = F_u / F_y \tag{2}$$

and

$$\mu = d_u / d_y \tag{3}$$

where F_y = yield base shear, F_u = maximum load reached in the test, d_u = displacement associated with F_u and d_y = displacement associated with F_y. In the research community there is no general agreement on the definition of both yielding and ultimate displacements and forces (Priestley et al. (2007)) and on the behaviour factor itself (Castiglioni (2016)). Amongst the different available approaches to evaluate the yielding parameters, for the study described in this paper, reference was made to ECCS n° 45 (1986) document. In this case, the yielding parameters are obtained as the intersection between the tangent at the origin of the curve, with slope E_t, and the tangent at the curve with slope $E_t/10$.

Table 1 provides the mean values of the over-strength Ω, the ductility ratio μ and the behaviour factor q obtained for the three levels of vertical loads Q. Higher values of behaviour factors are associated with lower levels of vertical loads. In detail, the q factor is more than 1.5 times greater in the case of Q = *1/3ESL* than in the case of Q = *ESL,* and the difference between the results obtained for the three levels of gravity loads is non-negligible. For all the levels of Q, the values of q are quite limited: they are the typical values for low dissipative structures. This is probably associated with the localisation of the plasticity at the first levels of the frames only. Comparable values of the behaviour factors were calculated by Castiglioni et al. (2014) and Kanyilmaz et al (2016b), on the basis of push-over tests conducted on four different racks with vertical loads comparable with the case of Q = *ESL*.

Table 1. Behaviour factors q obtained from the push-over tests results.

Q	Ω	μ	q
ESL	1.04	1.38	1.44
2/3ESL	1.06	1.52	1.61
1/3ESL	1.09	2.12	2.31

As a consequence, the values of behaviour factor shall be carefully adopted in design. For the two higher values of Q, the behaviour factors are approximately equal to 1.5, in agreement with the minimum value that can be assumed in accordance with EN 16681 (2016), for low dissipative design of moment resisting frames as racks. In general, the results obtained in this study are consistent with the values recommended by the standards. Nevertheless, it is worth remarking that the values are slightly different for the three levels of the gravity loads Q and that they were obtained from tests performed on racks hinged at the base. Considered the non-negligible influence of the different levels of gravity loads on the racks' global response, it would be desirable that specifications regarding this critical parameter will be provided in the future racks design standards.

7 CONCLUDING REMARKS

An extensive research on the response of industrial steel storage racks at both the component and global levels has been recently completed at the University of Trento. As part of the study, eight full-scale tests on two-bay four-level racks were performed. An innovative testing set-up was developed and adopted for the tests, which allows: i) maintaining the verticality of the applied loads during the tests even beyond the collapse of the structures, and ii) applying different loads at the different levels of the frames. This was made possible by the use of independent actuators. The full-scale experimental programme comprised of two vertical loads tests on two nominally equal specimens with an applied initial out-of-plumb, and six push-over tests in down-aisle direction. The push-over tests were carried out by maintaining constant vertical loads and by increasing the horizontal loads applied with an inverse triangular load pattern up to collapse. For the push-over tests, three values of vertical loads were selected on the basis of the experimental service load obtained from the vertical load tests. In both the vertical loads and the push-over tests, the tested racks exhibited the same collapse mode triggered by global instability, characterised by the sway of the structures and the plastic deformation of the beam-to-upright joints of the first levels of the frames. The push-over tests enable evaluation of the behaviour factors q of the racks, which ranged from 1.44 to 2.31. The obtained values confirmed the low ductility of this type of structures and were consistent with the design standard recommendations and with the findings of similar research projects. On the basis of the research, it was also recognised the lack of specifications regarding the racks full-scale testing in the current design standards, both for the testing procedure and for the evaluation of the testing results in order to provide guidelines for the design practice. In addition, the need of a general agreement on the definition of the behaviour factor q was also recognized.

8 ACKNOWLEDGEMENTS

The Authors would like to thank the Metalsistem S.p.A. for supporting the study and making available both the specimens and the testing tower for the full-scale tests.

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