An experimental investigation on base-plate joints of steel storage pallet racks

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Abstract

Adjustable storage pallet racks are framed structures commonly made of cold-formed steel profiles. The performance of these structures is strongly influenced by the beam-to-column and the base-plate joints behaviour. The key role of joints is even more significant in seismic loading conditions. The complexity of their non-linear and non-symmetric behaviour calls for their experimental characterisation both in monotonic and cyclic range. In recent years, attention has been paid to the study of beam-to-column joints, while the knowledge on the base-plate joints response is still quite limited. This gap is even more evident when the cross-aisle (transversal) direction and the cyclic range are considered. The research presented in this paper focuses on the monotonic and cyclic experimental response of a typical rack base-plate joint, tested both in down-aisle (longitudinal) and cross-aisle direction. The main features and outcomes of the study are presented and discussed.

Keywords: Steel storage racks, cold-formed steel, uprights, base-plate joints, cyclic and monotonic tests, experimental tests, cross-aisle and down-aisle directions.

1 Introduction

Adjustable storage pallet racks, widely adopted in the logistic field, are framed structures commonly made of cold-formed steel profiles [1]. The racks behaviour is affected by some peculiar features, such as the use of slender mono-symmetric perforated columns (the so-called uprights) [2] and of semi-rigid non-linear joints (beam-to-column and base-plate joints) [3]. The global stability of storage racks in the down-aisle (longitudinal) direction is typically provided by the sole degree of continuity of joints. In fact, racks are usually braced only in the cross-aisle (transversal) direction, while, in the down-aisle direction, due to logistic reasons, the stability is guaranteed by the semi-continuity of the joints. The key role of the joints becomes even more significant in seismic loading conditions. The response of all joints is non-linear and non-symmetric. In addition, in case of base-plate joints, another issue to be investigated concerns the influence on the joints' global performance of the level of axial load acting on the uprights.

The great variability of joints' geometry and the complex phenomena affecting their behaviour limited the development of general analytical models able to predict the moment-rotation response. In recent years, attempts to apply the well-known "component method" developed for traditional steel connections were made [4]. Although promising results were obtained, it should be stressed that the effectiveness of the proposed formulations is limited to configurations similar to the ones used for the development of these models. As a consequence, the main standards for the design of racking systems [5], [6], [7] adopt the "design by testing" approach, i.e. a mixed experimental-analytical design procedure

[8]. This method requires that tests are performed to evaluate the main design parameters of components, joints and sub-assemblies that should be used in the design check equations [9]. A similar approach is also required by the European seismic design standards for racks [10]. Therefore, as to the joints behaviour, experimental tests must be performed both in the monotonic and in the cyclic range.

In recent years, great attention has been paid to the study of beam-to-column joints, also in cyclic loading conditions [11], [12], [13]. On the contrary, the knowledge of the base-plate joints response is still rather limited [14], [15], [16]. This gap is even more significant if their key role is considered. In particular, this critical situation is more evident for the cross-aisle direction and the cyclic range [17], [18]. The study presented in this paper aims to contribute filling this gap.

An experimental and numerical study aimed at increasing the knowledge of the response of steel storage pallet racks in both static and seismic conditions has been recently carried out at the University of Trento [19]. The research investigated the racks' behaviour at both the individual component and the global level. Within this work, specific attention was paid to the response of the base-plate connections: a typical pallet rack base-plate joint was experimentally studied in monotonic and cyclic loading conditions, both in the down-aisle and the cross-aisle direction. The main features and outcomes of the experimental campaign are here presented and discussed.

2 Experimental programme

The commercial base-plate joint considered in the study is presented in Figure 1. The joint is made of an upright with an open mono-symmetric cold-formed perforated section with a thickness of 1.45 mm and a mono-symmetric cold-formed base-plate 4 mm thick. Both components are of steel grade S350GD. Eight M8 class 8.8 bolts provide the inter-connection, while the assembly is connected to the floor by means of four Hilti HSA M16 chemical bolts.

The experimental programme investigated the joint's response in both the cross-aisle and the down-aisle directions. Tests were performed in the monotonic and in the cyclic range. Three levels of axial load were considered: 3%, 27% and 43% of the collapse load obtained by preliminary compression tests on the assembly. In the present paper, the results related to a typical service loading condition, i.e. 27% of the collapse load, are presented.

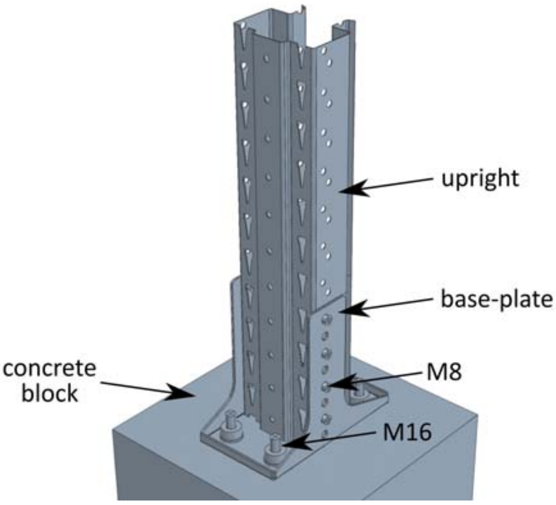

Figure 1. The base-plate joint

The experimental set-up showed in Figure 2 was designed and built up in accordance with the EN15512 [7] recommendations.

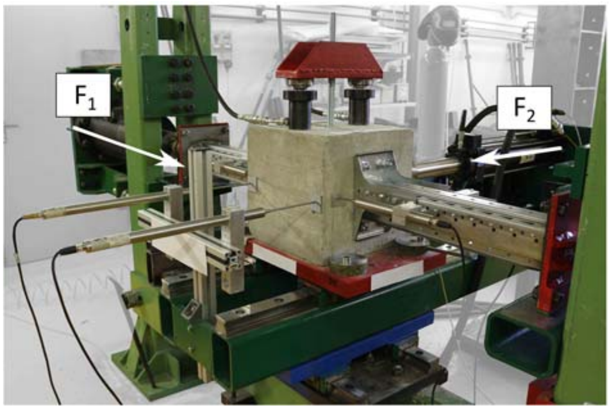

Figure 2. Experimental set-up

Each test was performed on two assemblies, each one composed by a 560 mm length upright completed with the base-plate. The base-plates are connected to the opposite faces of a concrete cube, which simulates the floor surface, and the free ends of the uprights are hinged to the testing rig. The loading comprises two steps: an axial load

(F_1) is first applied to the uprights and then a transversal force (F_2) is transmitted to the concrete cube, by using two hydraulic jacks. The concrete block is free to move in F_2 direction, while its rotation is prevented. During the tests, the force F_1 is held constant, while force F_2 is increased up to the collapse of the specimens. Both forces, F_1 and F_2, contribute to the development of a bending moment acting on the base-plate joints. Displacement transducers were used to measure the displacement of the concrete block in the F_2 direction so allowing the evaluation of the second order bending moment and to calculate the rotation of the base-plate joints. Moments and rotation were evaluated on the basis of the EN15512 [7] recommendations.

As already mentioned, the programme comprised monotonic and cyclic tests. In monotonic tests the three configurations presented in Figure 3 were considered. In detail, configuration A refers to the joint's behaviour in the down-aisle direction, while configurations B1 and B2 are related to the cross-aisle direction. For each testing configuration three tests were performed. The monotonic tests results allowed defining the cyclic loading history, both for the down-aisle and the cross-aisle direction (configuration B). At this aim, the ECCS cyclic loading protocol [20] was taken as a reference. In cross-aisle direction, being the joint's behaviour non-symmetric, a non-symmetric loading history was identified.

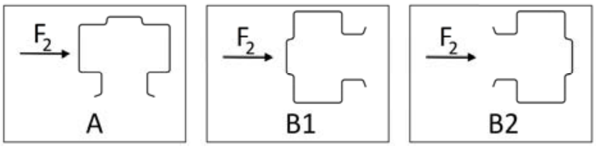

Figure 3. Tested configurations

2.1 Tests in down-aisle direction

2.1.1 Monotonic tests

Figure 4 shows a typical collapse mode exhibited by the joint when monotonically tested in the down-aisle direction. Local bow deformations of the upright due to the contact with the base-plate and at the end of the base-plate "flanges" triggered the collapse. The moment-rotation relationships for the three tests are plotted in Figure 5. In the figure, the moment is normalised with respect to the flexural upright bending resistance, i.e. $W_g \cdot f_y$, where W_g is the gross section modulus and f_y is the nominal yielding strength of the steel. Notwithstanding the complexity of the testing set-up and of the joint's performance, the experimental curves show a rather limited scatter. The curves are characterised by an initial elastic behaviour approximately up to m=0.6, followed by a plastic hardening branch, up to the collapse.

Figure 4. Collapse mode for monotonic tests in the down-aisle direction (configuration A)

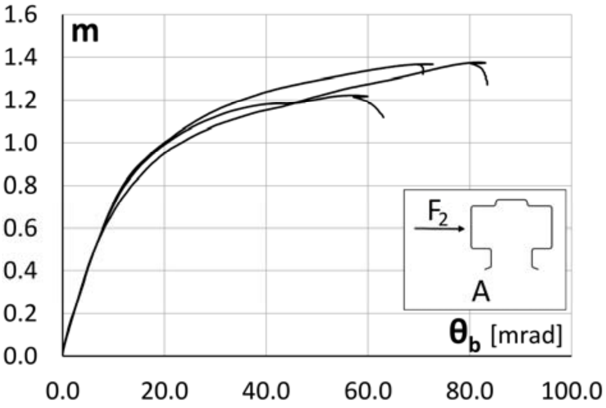

Figure 5. Normalised moment vs. rotation curves for monotonic tests in the down-aisle direction (configuration A)

2.1.2 Cyclic tests

A similar collapse mode was observed in the monotonic and in the cyclic tests (see Figure 4 and Figure 6).

The normalised moment vs. rotation curves for the three cyclic tests are presented in Figure 7. A quite limited scatter of tests results can be observed. In addition, as expected, the symmetric behaviour of the joint was experimentally confirmed. It should be noted that the cyclic curves pointed out a limited pinching effect.

Figure 6. Collapse mode for cyclic tests in the down-aisle direction (configuration A)

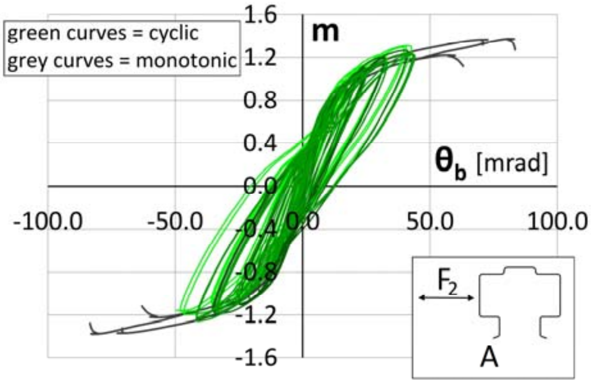

Figure 7. Normalised moment vs. rotation curves for cyclic tests in the down-aisle direction (configuration A)

For comparison purposes, in Figure 7, the monotonic test curves are also reported (in grey colour). Due to the symmetric behaviour of the joint, the monotonic curves obtained for positive moments and rotations were also plotted in the negative moment-rotation field. The good agreement between monotonic and cyclic tests results is apparent.

2.2 Tests in cross-aisle direction

2.2.1 Monotonic tests

The non-symmetric behaviour of the joint in the cross-aisle direction is apparent when the observed collapse modes are compared (see Figure 8 and Figure 9). Figure 8 is related to the B1 configuration, i.e. with the web of the upright under compression, and shows remarkable deformations of both the upright and the base-plate localised in the connection area. In the configuration B2, i.e. with the flanges of the upright subjected to compression, the collapse is triggered by a "distortional" deformation of the upright (Figure 9).

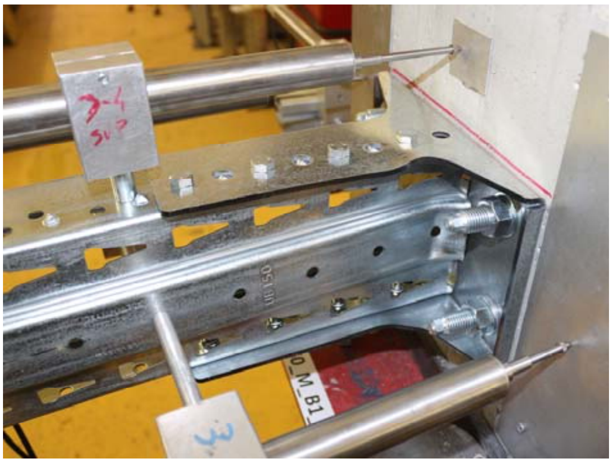

Figure 8. Collapse mode for monotonic tests in the cross-aisle direction (configuration B1)

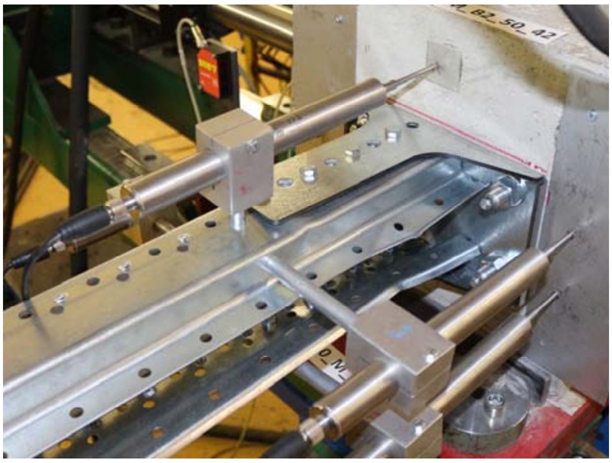

Figure 9. Collapse mode for monotonic tests in the cross-aisle direction (configuration B2)

The normalised moment vs. rotation curves for the configuration B1 and B2 are reported in Figure 10 and Figure 11, respectively. In both cases, the significant non-linearity of the joints' behaviour is apparent. The scatter of the results is limited also for these configurations. The analysis of the two figures points out a comparable bending moment capacity but a fairly different rotational capacity of the joint for the two configurations.

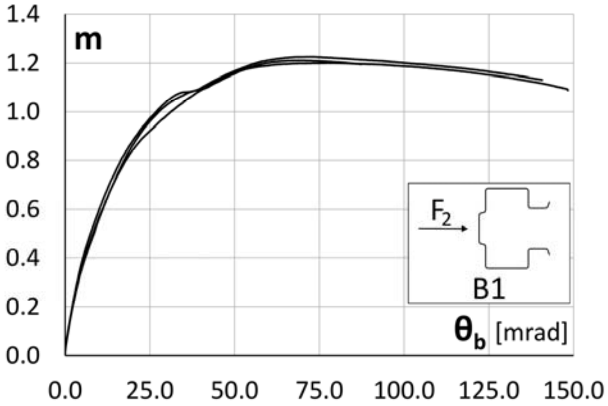

Figure 10. Normalised moment vs. rotation curves for monotonic tests in the cross-aisle direction (configuration B1)

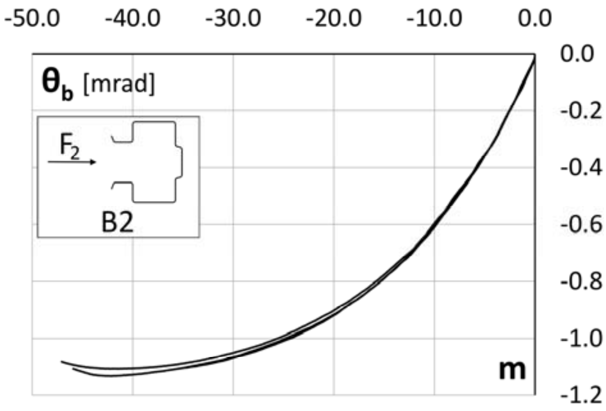

Figure 11. Normalised moment vs. rotation curves for monotonic tests in the cross-aisle direction (configuration B2)

2.2.2 Cyclic tests

The specimens cyclically tested in the cross-aisle direction exhibited a collapse mode which is a sort of combination of the ones obtained for the B1 and the B2 monotonic testing configurations (Figure 12): remarkable deformations of the flanges were first observed, followed by deformations of the web of the upright.

As expected, the response of the joint was non-symmetric as shown in Figure 13. In the figure, no remarkable pinching effect is visible. Moreover, the comparison with the monotonic experimental results (grey curves in Figure 13) points out the substantial reduction of the rotational capacity of the joint when it is cyclically loaded.

Figure 12. Collapse mode for cyclic tests in the cross-aisle direction (configuration B)

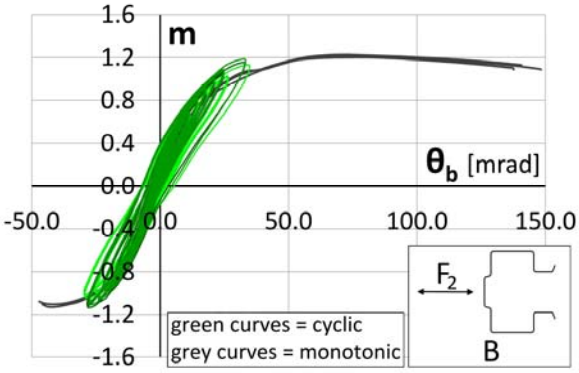

Figure 13. Normalised moment vs. rotation curves for cyclic tests in the cross-aisle direction (configuration B)

2.3 General remarks

Tests results show that, for the considered level of axial load and independently on the testing configuration, the upright revealed to be the weakest component of the joint assembly. In addition, it is worth remarking that in all the cases no deformations of both the connection of the base-plate to the concrete block and of the concrete block itself were observed.

In the case of monotonic tests, Table 1 enables a comparison between the tests results. In the table, the normalised average values of the initial stiffness k_m and of the maximum bending moment m_m are reported.

Table 1. Initial stiffness and maximum bending moment for monotonic tests

Configuration	**k_m [1/mrad]**	**m_m [-]**
A	0.066	1.32
B1	0.042	1.21
B2	0.053	-1.12

To calculate the initial stiffness, reference was made to the energetic criterion suggested by the EN15512 standard [7] and depicted in Figure 14.

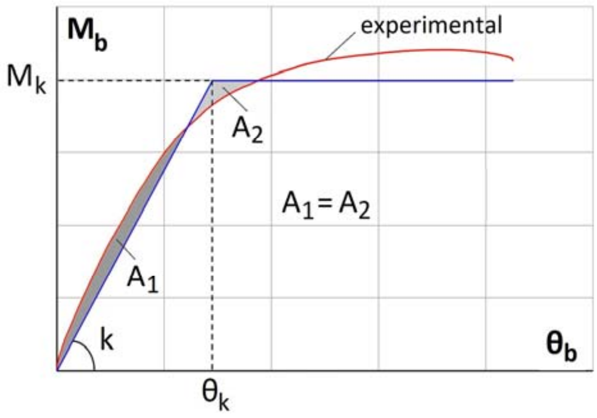

Figure 14. EN15512 standard [7] criterion for the evaluation of the joint initial stiffness

In terms of both the stiffness and the resistance, configuration A (down-aisle direction) provides the best performance. This finding is consistent with the need of providing an adequate degree of continuity to the rack in the down-aisle direction, where usually no bracing systems can be provided and hence, racks' lateral stability depends on the beam-to-column and base-plate joints' response. As to the cross-aisle direction, Table 1 points out a quite limited difference in terms of bending resistance between the two configurations, which is equal to 7.4% if configuration B1 is assumed as reference. A higher difference is associated with the initial stiffness: configuration B2 has an average initial stiffness 26.2% higher than the one of configuration B1.

A comparison between the cyclic tests results was performed in terms of cumulated dissipated energy vs. cumulated joint rotation, as shown in Figure 15. The joint has a more dissipative behaviour in the down-aisle direction, i.e. configuration A, with respect to the cross-aisle direction, i.e. configuration B.

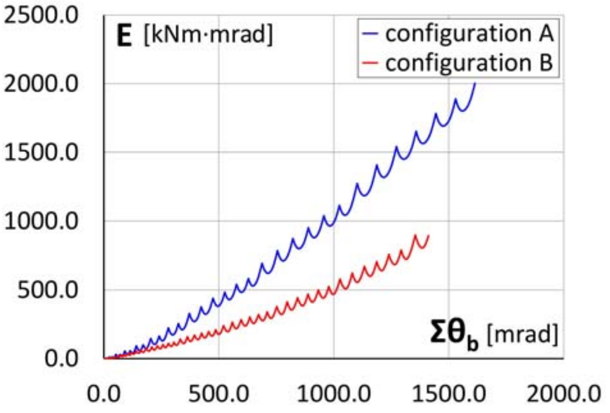

Figure 15. Energy vs. cumulated rotation for the cyclic tests

3 Conclusions

As part of a wide research focusing on the performance of steel storage pallet rack structures, an experimental study of the response of a typical base-plate connection was performed. The experimental programme comprised of monotonic and cyclic tests, both in the down-aisle and the cross-aisle direction. The joint's response was investigated by considering three levels of axial load acting on the upright. Tests results pointed out the remarkable influence of the axial load on the collapse modes, the collapse loads and the joint's rotational capacity. Furthermore, cyclic tests highlighted a remarkable pinching effect in the case of the lowest level of axial load, for both A and B configurations. In this paper, the outcomes of the tests associated with the intermediate axial load level, equal to 27 % of the collapse load obtained by pure compression tests, are reported. Tests results pointed out:

- collapse modes mainly associated with the upright's failure. Only in the cross-aisle direction, deformations of the base-plate were also observed. In all the cases the concrete block and the connection between the base-plate and the concrete itself showed no deformation;
- a remarkable non-linear joint's response in both the down-aisle and the cross-aisle direction;
- a non-symmetric behaviour of the joint in the cross-aisle direction;
- a limited pinching effect exhibited during the cyclic tests;
- a better performance of the joint in terms of initial stiffness, bending resistance and dissipative capacity when bent in down-aisle direction. This behaviour is consistent with the need of providing a sufficient rack's lateral stability in the down-aisle direction, given that bracings are usually placed in the cross-aisle direction only.

4 Acknowledgements

The authors gratefully acknowledge the work by the laboratory technicians of the University of Trento Stefano Girardi and Marco Graziadei and the contribution of the company Metalsistem S.p.A. that provided the tested specimens.

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