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EXPERIMENTAL INVESTIGATION OF BEHAVIOR OF THE STEEL STORAGE RACK FRAMES STABILIZED BY SINGLE-SIDED SPINE BRACING

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Abstract. *High-rise racks are cold-formed thin-walled framing structures which can provide much higher storage capacities while taking only similar footprints compared with ordinary steel storage racks. The structural layout of the high-rise racks is characterized by the single-sided spine bracing located at a short horizontal distance away from the main rack frames. Such structural layout, however, triggers complex global sway performance of the racks under vertical loads which has not been well investigated. This paper presents an research program in which the buckling behavior of eight single-storey rack frames enhanced by single-sided spine bracing was experimentally investigated. A test setup was carefully designed which enabled the applied vertical loads to move freely along with the three-dimensional deformation of the tested rack frames at all times. The test observations suggested that the braced rack frames exhibited a three-dimensional flexural-torsional sway mode under vertical loads. Both the configurations of the spine bracing and the upright frame bracing had a noticeable influence on the buckling strength of the braced rack frames in testing.*

1 INTRODUCTION

Steel storage racks are cold-formed thin-walled framing structures which carry pallets or other merchandises. In general, the ordinary racks and the high-rise racks are two major applications of the racking systems in the logistic industry. Ordinary racks usually appear in traditional warehouses and retail areas. They may have four or five load levels and commonly carry a limited number of pallets. The structural layout of a representative ordinary rack is illustrated in Figure 1. It can be noticed that the ordinary racks are usually not braced in the down-aisle (bay) direction. The rack frames are “stiffness regular” both in plan and in elevation in the down-aisle direction. Generally, the performance and the design of such ordinary racks are comparable to the moment-resisting convensional steel building frames.

Compared with ordinary racks, the high-rise racks are able to provide considerably higher storage capacities while taking only similar footprints. Thus, the high-rise racks are widely used in the mordern warehouses worldwide in recent years. The structural layout of a representative high-rise racks is illustrated in Figure 2. Different from the ordinary racks, the main rack frames of the high-rise racks commonly require additional stiffening in the down-aisle direction. As shown in Figure 2(a), the longitudinal bracing, however, only appears on the back side of the main rack frame, so that the pallets can be placed on the pallet beams of the main rack from the opposite side (i.e., the front side). As such, the longitudinal bracing in the down-aisle direction is often referred to as “spine bracing” in the rack structures. Considering that an overhang from the pallet beams is absolutely necessary for the storage of the pallets,consequently the spine bracing is usually located at a short horizontal distance away from the rear rack frame to be stabilized. The stabilizing forces are therefore transmitted to the spine bracing through a rack-to-spine-bracing joints (see Figure 2(b)). It is obvious that the high-rise racks stabilized by single-sided spine bracing is not stiffness regular in plan along the down-aisle direction [1]. There is little doubt that such structural layout would result in a complex three-dimensional performance of the rack frames.

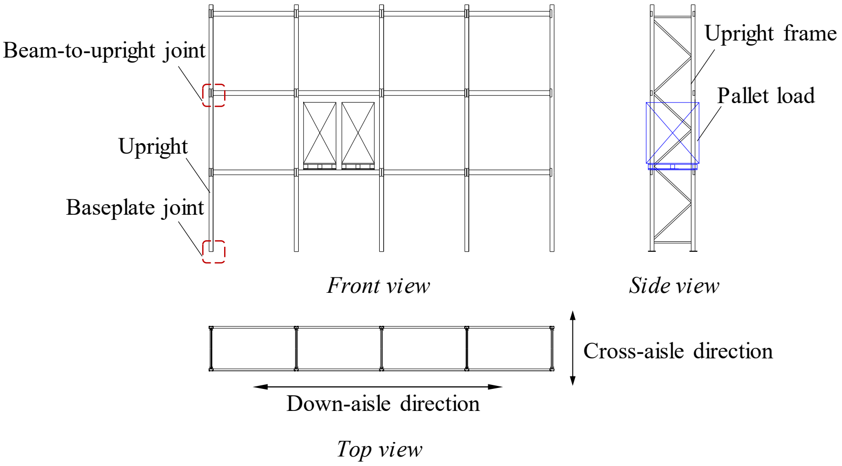
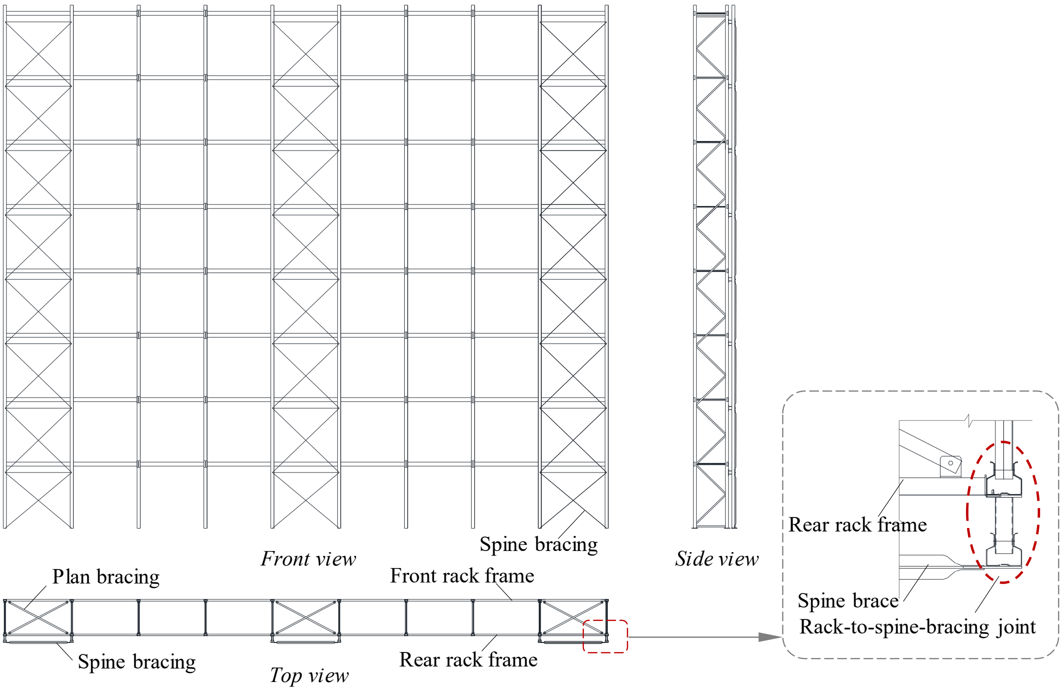


Figure 1: Structural layout of a ordinary rack.



(a) Global rack layout **(b)** Zoom-in view

Figure 2: Structural layout of a high-rise braced rack.

Literature review indicates that the structural performance of the high-rise racks is hitherto poorly understood. Currently available rack design codes [1-4] neither provide adequate design guidelines nor detailed testing methods associated with the high-rise racks. Even though the numerical studies performed by Teh *et al.* [5], Chen and Wu [6], Yin *et al.* [7,8], and Huang and Zhao [9] reasonably captured the eccentricities between the main rack frames and the adjacent spine bracing, the analysis models established in these studies, however, were to a large extent simplified (i.e., using beam elements instead of shell elements, not considering the actural force transfer mechanisms of various types of joints or the eccentricities between different structural members, and etc.), making the corresponding numerical results less reliable.

It is well acknowledged by the scientific and technical communities that the "design by testing" method may be currently the most reliable approach in evaluation of the actural performance of a high-rise rack. In this aspect, the performace of the one-storey and four-storey full-scale rack frames stabilized by single-sided spine bracing subjected lateral loads were experimentally established in Seisracks2 project [10, 11]. However, it is pointed out that, despite the fact that the high-rise racks carry heavy merchandises and are prone to buckling, the behavior of the high-rise racks subjected to vertical loads has not been experimentally established yet.

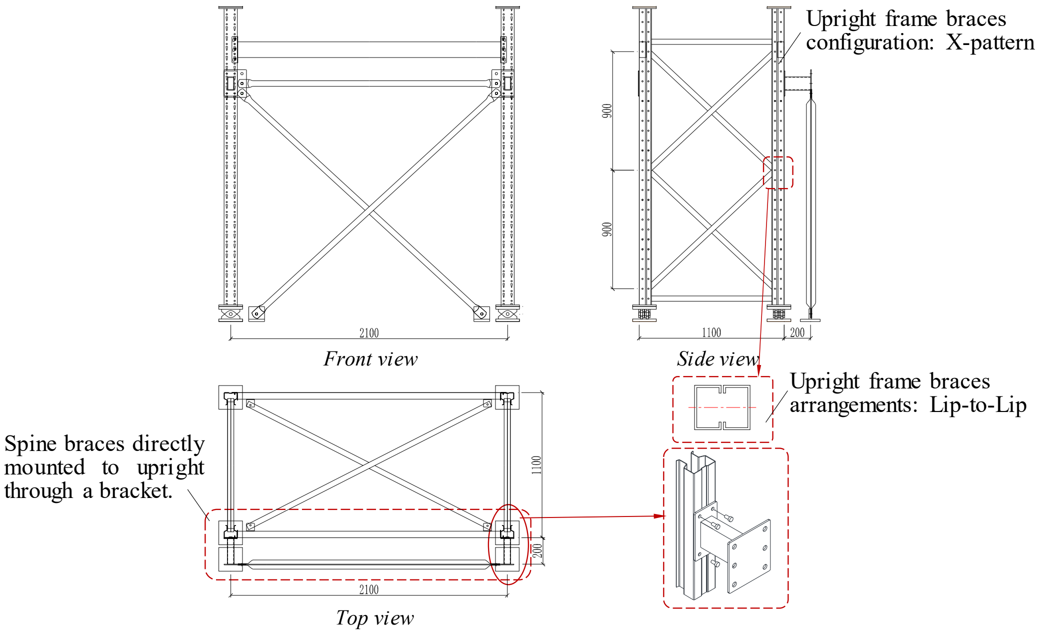
The aim of this paper is to experimentally investigate the buckling behaivor of the steel storage rack frames stabilized by single-sided spine bracing under vertical loads. The test program involves eight single-storey braced rack frames. The influence of various structural details, including the spine bracing configurations and the upright frame bracing configurations, on the buckling performance of the braced racks are experimentally evaluated. All the tested frames are subjected to vertical loads and are loaded to failure. The three-dimensional sway modes and the failure mechanisms of the tested rack frames are highlighted.

2 TESTED RACK FRAMES

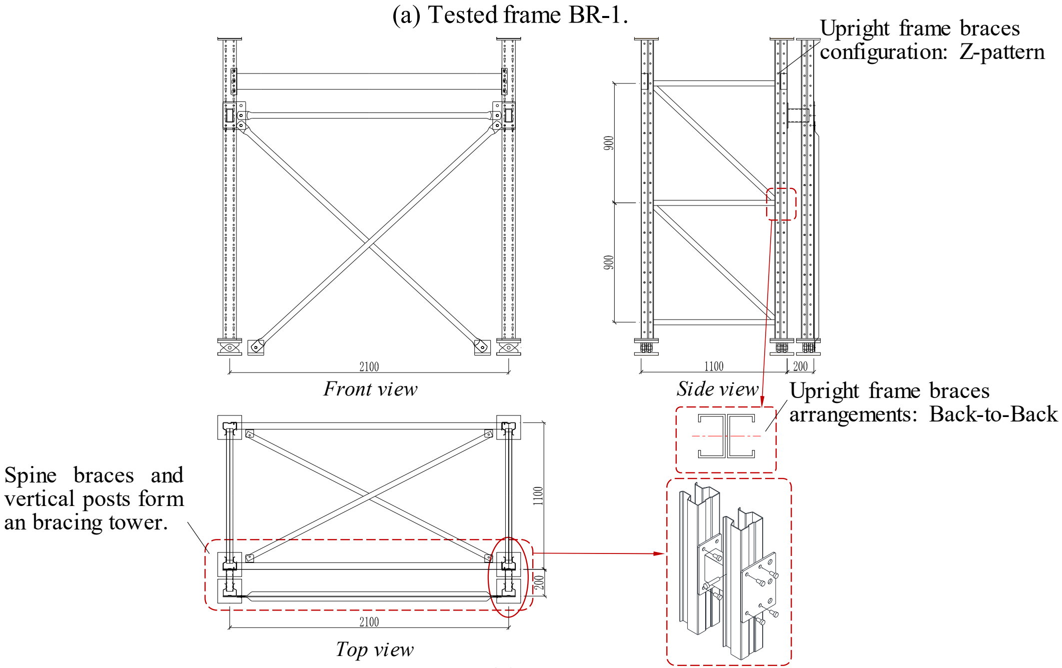
The test program involved eight single-storey one bay rack frames. Each rack frame was stabilized by single-sided spine bracing. The general layout and the structural details of two representative tested rack frames are illustrated in Figure 3. In the down-aisle direction, the tested frames had a bay width of 2100 mm and a storey height (i.e., the distance between the hinge at the upright bases and the center line of the pallet beam) of 2000 mm. Two spine bracing configurations were experimentally considered in the study. The spine braces either was directly mounted to the corresponding main rack frame through a bracing bracket (see Figure 3(a)), or formed an independent bracing tower together with a pair of vertical posts, which was then attached to the main rack frame through brackets (see Figure 3(b)). The structural details of the associated rack-to-spine-bracing joints are schematically shown in Figure 3(a) and (b), respectively. The front rack frame was braced against the rear rack frame though a pair of C-section diagonal braces (i.e., plan bracing).

In the cross-aisle direction, a pair of uprights were braced against each other forming so an upright frame which was 1100 mm in depth. The upright frames comprised of two bracing panels, each panel having a height of 900 mm. The bracing members presented either in X-pattern (see Figure 3(a)) or in Z-pattern (see Figure 3(b)). The C-section bracing members were arranged either in lip-tp-lip (see Figure 3(a)) or back-to-back (see Figure 3(b)) orientations. Considering the combinations of the braces patterns and the orientations, a total of four upright frame bracing configurations were involved in the test program. The clearence between the spine bracing plane and the rear rack frame equaled to 200 mm.

Except for the structural layout, all the tested rack frames were assembled using nominally identical structural members. The uprights used a C-shaped profile having stiffened web and folded flanges with tips. The total depth of the web, the total width of the flanges, and the wall thickness of the section equaled to 100 mm, 94 mm, and 3 mm, respectively. The pallet beams have a box section which was 120 mm in height, 50 mm in width, and 1.5 mm in thickness. The beams were connected to the uprights through a beam-end-connector with three tabs and one locking bolts. The plan braces and the upright frame braces used a 40 mm×24 mm×1.5 mm C-section with lips. The spine braces, including the horizontal members and the diagonal members, used a circular hollow section. Prior to testing, the geometric imperfections of the rack frames were measured.



(a) Tested frame BR-1.



(b) Tested frame BR-8.

Figure 3: Structural details of representative rack frames in the test program.

3 TEST RIG

3.1 Test setup

Generally, the test setup is designed such that the idealized loading and boundary conditions are realized at all loading steps. Considering that the sway of the rear rack frame and the front rack frame along the down-aisle direction might be different, as shown in Figure 4, two actuators were employed in the experimental program and applied vertical loads to the front rack frame (Actuators #1) and rear rack frame (Actuators #2), respectively. There is no doubt that restraining the applied loads in the vertical direction throughout the loading procedure was the key to the success of testing. As such, recognizing that the tested rack frame might exhibit complex three-dimensional sway during the tests, the fixing ends of both actuators were mounted to a two-way sliding support which consisted of two groups of factory-made guide rails laying perpendicular to each other. The two-way sliding supports enabled the Actuators #1 and #2 move freely along with the three-dimensional deflection of the front rack frame and the rear rack frame independently.

The loading end of the actuator was connected to a rigid spreader beam through a pin (ball bearing).The applied load in each actuator was recorded using a load cell. The top and end sections of each upright were connected to the spreader beam and a rigid base through a hinge, respectively.

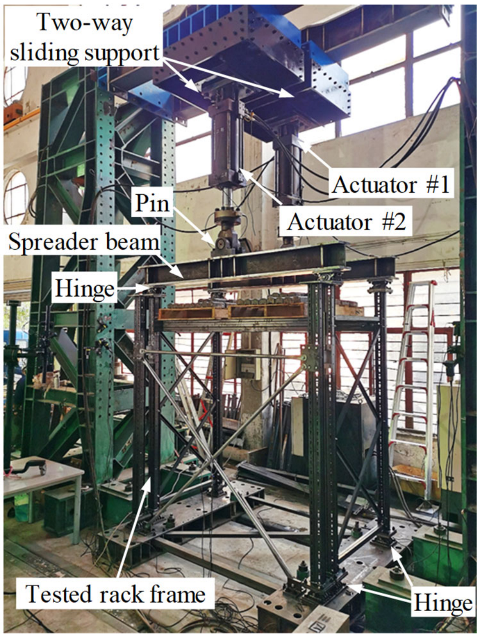


Figure 4: Test setup.

3.2 Displacement measurements

A total of 12 displacement transducers were used to record the response of the tested rack frame under vertical loading. As shown in Figure 5, transducer pairs D1&D2 and D3&D4 measured the deflection of the rear rack frame and the front rack frame along the down-aisle direction, respectively. Transducer D5 and D6 recorded the out-of-plane deformation of the uprights in the front rack frame. Transducers D1 thru D6 were positioned at the height of the centerline of the pallet beams. Transducers D9 and D12 measured the in-plane sway of the spine bracing at the height of the horizontal spine bracing member. Transducer pairs D7&D8 and D10&D11 were used to record the lateral deflection of the bracing bracket on each side. It is pointed out that all of the transducers were positioned at a considerably long distance away from the corresponding measurement point, so that the undesired geometric effects induced by the frame movements during the tests on the transducer readings would be best eliminated.

3.3 Test procedure

Before the start of the test, a pair of 500 kg pallets were placed on the tested rack frame, so that the gaps between the beam-end-connectors and the uprights would be closed. During the tests, the two actuators were controlled using a hybrid program. At the beginning, both the actuators were operated using a load-controlled program. The applied vertical load in each actuator was kept consistent at each loading step and increased at a rate of 1.0 kN/min. When the total vertical load surpassed 2/3 of the estimated buckling strength, Actuator #1 was switched from the load-controlled program to a displacement-controlled program, whereas, the

Actuator #2 was switched to a modified load-controlled program, in which the applied load in Actuator #2 was kept consistent with the real-time applied load in Actuator #1. The test was terminated when the tested rack frame exhibited a peak load. However, in practice, since the actuators were able to slide along with the sway of the rack frame, the actuators were unable to hold the rack frame at a stable position when the ultimate load was reached. Consequently an uncontrolled collapse of the rack frame occurred shortly after passing the ultimate load.

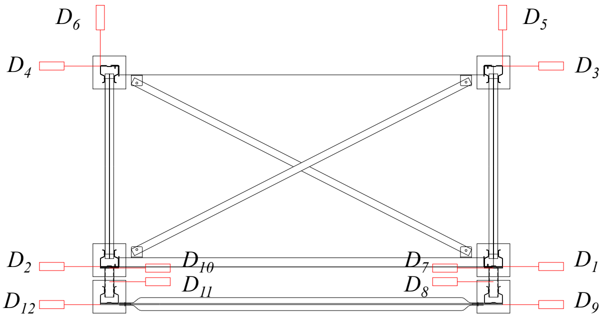


Figure 5: Displacement transducer measurements.

4 EXPERIMENTAL OBSERVATIONS

4.1 Frame behavior and failure

Figure 6 shows the load-deformation relations of a representative tested rack frame. The sway deflections of the front rack frame (Δ_{FF}), rear rack frame (Δ_{RF}), and spine bracing (Δ_{SB}) along the down-aisle direction are plotted against each other. It can be noticed that the sway deflection of the front rack frame was considerably different from the rear rack frame, indicating that the stiffness of the plan bracing between the front and rear rack frames was not sufficient to uniform the sway deflections of the front rack frame and the rear rack frame. The difference between the rear rack frame deflection and the spine bracing deflection, however, suggested that the rack-to-spine-bracing joints compromised the effective stiffness of the spine bracing. The differences between the sway deflections of the rack frames and the spine bracing may be observed from Figure 7(a).

In addition to the sway of the front and rear rack frames along the down-aisle direction, as evidently clear from Figure 7 (c), the uprights exhibited noticeable out-of-plane deformation as well, which resulted in the upright frames experiencing transverse shear deformation along the cross-aisle direction and the global rack frames exhibiting a three-deimensional flexural-torsional sway mode (see Figure 7 (b)).

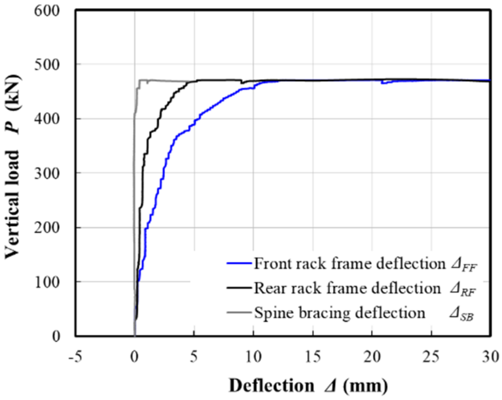


Figure 6: Load-deformation relations of a representative tested rack frame.

As can be noticed from the load-deformation relations in Figure 6, the tested rack frame experienced a sudden failure well after the instant the ultimate load was reached, followed by an uncontrolled sway of the rack frames. As a general statement, the collape of the rack frames was initiated by the sway buckling of the entire frame. In some circumstances, the distortional buckling in the uprights might happen along with the sway of the global rack frame (see Figure 7(d) and (e)).

(a) (b) (c) (d) (e)

Figure 7: Sway and failure mode of a representative tested rack frame.

4.2 Influence of the structural details on the buckling strength of rack frames

Comparing the sway performance and the buckling strength of various tested rack frames, the following observations could be obtained.

(1) *Influence of the spine bracing configurations*. The test observations suggested that, in the scenarios where the rack frames were braced by independent spine bracing towers, the bracing brackets between the main rack frame and the adjacent spine bracing only experienced one-directional lateral bending. Whereas, in the scenarios where the spine braces were directly connected to the rack frames through the brackets, the brackets would experience significant bi-directional bending, which further compromised the effective stiffness of the bracing bracing. Consequently, the rack frames braced by independent spine bracing towers commonly exhibited a higher buckling strength than the rack frames with spine braces directly mounted to the bracing brackets.

(2) *Influence of the upright frame bracing pattern*. Since the tranverse shear stiffness of the upright frames with X-pattern braces was higher than the upright frames with Z-pattern braces, in the tests the rack frames with X-pattern upright frame braces generally exhibited smaller out-of-plane deflection than the rack frames with Z -pattern braces. As a result, it was not surprising that the strength of the tested rack frames with X-pattern upright frame braces was consistently higher than the rack frames with Z-pattern braces.

5 CONCLUDING REMARKS

High-rise steel storage racks are cold-formed thin-walled slender framing structures which are characterized by the longitudinal spine bracing appearing only on one-side of the main rack frames to be stabilized. Even though the high-rise racks are widely used in the logistic industry and are able to carry a large number of pallets or other heavy merchandises, the performance of such high-rise storage structures under vertical loads, however, are hitherto poorly understood.

This paper presents an experimental research program in which 8 single-storey braced steel storage rack frames were loaded vertically to failure. A test setup was carefully designed so that the desired loading and boundary conditions could be realized at all loading steps. In the tests two actuators were employed to apply vertical load to the front and rear rack frames, respectively. The fixing end of each actuator was mounted to a two-way sliding support which enable the actuators to move freely along with the three-dimensional sway of the rack frames.

It is generally stated that all of the tested rack frames stabilized by single-sided spine bracing experienced a three-dimensional global flexural-torsional sway under vertical loads. In the down-aisle direction, the deflection of the front rack frames was consistently larger than the rear rack frames. The shear deformation between the rear rack frame and the adjacent spine bracing could also be observed. In addition to the rack frames deflection along the down-aisle direction, the uprights of the tested rack frames experienced noticeable out-of-plane deformation, which consequently led to the entire braced rack frames exhibiting a combined translational and rotational sway mode. In the meantime, the test observations suggested that both the spine bracing configuration and the upright frame configuration played an important role in determining the buckling strength of the steel storage racks. It is generally stated that future research works characterizing the influence of various structural details assocaited with the spine bracing and upright frame configurations on the high-rise rack buckling strength are essential for the practical design.

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