BEHAVIOR OF INDUSTRIAL STEEL STORAGE RACKS UNDER TRIAL LOAD

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UDK: 624.042:517.9
DOI: 10.14415/konferencijaGFS2019.028

Summary: *This paper presents the results of testing of industrial steel rack subjected to maximum trial load. Testing confirmed that the overall behavior of the tested structure under exploitation load is highly dependent on the stiffness properties of beam-to-column connection. The obtained results showed that conventional approach to structural modeling by applying linear models and idealized behavior of connections can lead to wrong conclusion on its structural behavior and unsafe design of steel racks.*

Keywords: *Industrial steel rack, testing, trial load, structural behavior*

1. INTRODUCTION

In last few decades, due to growth in overall consumption, and trend of big-box stores, an increasing use of steel storage racks has been noticed. In traditional shops, retailers used to store goods outside the retail space, i.e. outside the direct reach of consumers. In contrast, in a lot of modern stores, shoppers are in a close proximity of pallet racks, whose height and weight vary, depending on the actual purpose, but their failure can, nevertheless, present a risk to life safety.
Rack structures are ordinarily manufactured by specialized companies, and their design differences depend on manufacturer's tools and in-house patents. Commercial reasons incite the manufacturers to design and produce rack components with minimum weight.
Although adjustable steel racks are most usually common choice for storing goods and products [1], there are other alternatives such as drive-in and drive-through rack systems, shuttle racks, etc. The sub-types of commercially available steel storage rack structures are push back racks, cantilever racks, narrow aisle racks, gravity flow racks and double deep pallet racks. The drive-in and drive-thru rack systems incorporate rails throughout the depth of the rack for placing the pallets.
The majority of steel rack structures are low or medium rise, and when the rack total height is less than 15-20 m [2], storage rack are usually located inside a building, which protects

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them from climatic loads, implying that only imposed, accidental and seismic loads should be considered [3].

Adjustable steel rack's structural system usually consists of the following cold-formed steel components [5]: upright (or upright column, in the following text referred to as "column"), pallet beam, frame bracing, beam-end-connector (BEC) and some sort of additional bracing.

Prediction of the structural behavior of pallet racks is difficult because it is affected by the particular geometry of their structural components: members made from thin-walled, open-section profiles with high slenderness (hence prone to global, local and distortional buckling problems), beam-to-upright and base-plate joints exhibiting almost inevitably non-linear behavior [4]. Two major problems that render the design of steel racks very demanding are columns and beam-to-column connections.

Columns are most commonly mono-symmetric C shaped thin walled profiles with perforations or slots equally distributed along the web, so the tabs of BEC can be inserted in the holes, creating so-called speed-lock connection between pallet beam and the column. The beams are connected to uprights by end-connectors, which are pre-welded onto the ends of beams. The end-connector's tabs are inserted into the upright's perforations and the beam is pushed down to engage and connects the beam to the upright [6], Figure 2.

Furthermore, the rack structural system differs in two principal directions that are called cross-aisle (transverse) and down-aisle (longitudinal) directions. Braced frames are used as bearing system for horizontal loading in the former, and moment resisting frames are used in the latter direction.

Initially, steel racks were considered as working equipment, and hence their design did not comply with standard building codes. Later, market requested racks capable of withstanding seismic actions, both for safety reasons and to protect the goods [7]. Worldwide, pallet rack design is defined by different codes: in Europe - EN15512 [8], in USA - Rack Manufacturers Institute (RMI) specifications [9], in Australia - AS4084 [10]. All of these codes include tests of structural elements, even in a design phase. A Comparative review of analysis methods recommended by these codes is given in [11].

Current situation in Serbia is such that steel racks have an ambiguous treatment in practice. Manufacturers usually produce them under some sort of license what, at least, ensures their initial quality. However, structural design is sometimes performed or verified by structural (civil) engineers and sometimes by mechanical engineers. Former often lack the awareness of specific effects of production on the bearing capacity and stability of steel racks, while latter often lack the expertise in designing such types of structures that exhibit behavior closer to one of the building structures. Quality control of these structures is finally governed by the demands related to structural safety and maintenance, which, in most cases, lead to requests made by the owner and/or manufacturer for tests under trial loads to be conducted as formal prerequisite for the official technical audit prior to issuing of the use permit. This paper present one such test that shows the complexity of the structural behavior of steel storage racks under heavy loads and corroborates the need to investigate it more thoroughly.

2. DESCRIPTION OF THE TESTED STEEL RACK

Steel rack structure that was tested within this study is a typical representative of these structures. The owner of the rack, P.E. "Parking Servis" Belgrade, made the request for these racks to be tested as a part of the regular maintenance activities during which it was discovered that no technical data exists for these racks with regards to their load bearing capacity.

The racks that were subjected to trial load tests were constructed in 2007 and, in August 2018, they were subjected to detailed examination and restoration. Steel rack elements were constructed from steel plates (S235JR) of various thicknesses (2-5 mm). The steel plates, in this case, were cold-formed and joined by means of welding and/or bolted connections. Surface cover was applied through electrostatic coating and baking.

Each steel rack, Figure 1, consists of following elements:

- horizontal beam that serves as a palette support. This element is constructed as cold-formed profile 120x40x2,5mm;
- vertical columns with perforations used for beam-to-column connections. This element is constructed as rectangular cross section with dimensions of 100x55mm and with wall thickness of 2mm;
- truss members between two columns. These elements were constructed as a cold-formed rectangular cross sections with dimensions of 40x20x2, Figure 3;
- bottom steel plate, 5 mm thick, with M12 anchor bolts, Figure 3;
- vertical and longitudinal barriers, Figure 1.

Tested steel racks were fixed to the concrete floor of the warehouse with anchors and steel plates. The floor had to meet specific requirements such as: maximum inclination that is smaller than 3 mm on 1000 mm, 10 cm thickness and appropriate compression stiffness.

Figure 1. Fully loaded steel rack during testing [12]

Schematic description of beam-to-column and column-to floor connection is shown on Figures 2 and 3.

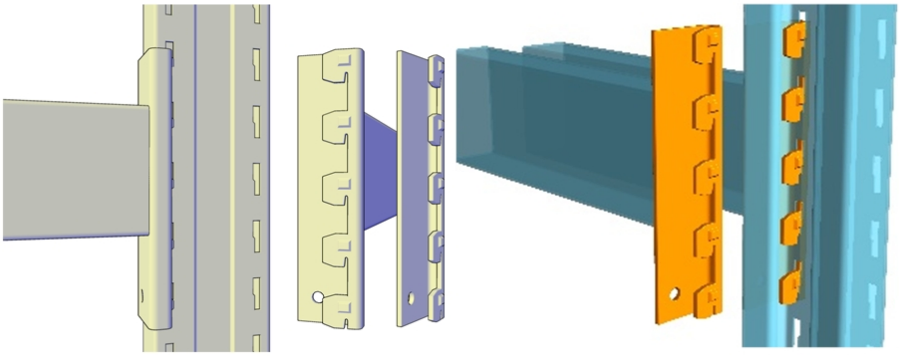

Figure 2. Beam-to-column connection

Figure 3. Tested steel rack: beam-to-column connection (left) and column-to-floor connection (right)

3. TESTING PROCEDURE

Load demand for considered steel racks and free vertical distance of 145 cm between beams was up to 3000 kg of uniformly distributed pallets on each horizontal shelf. In total, design load was up to 9000 kg on horizontal beams and 3000 kg on the floor beneath the first shelf.

Testing program consisted of following activities:

- detailed visual inspection of all steel rack elements;
- control of overall dimensions of the steel rack;
- control of cross section dimensions for all structural elements and, if applicable, determination of the irregularities;
- if applicable, determination of critical sections and/or structural damages;
- testing of the structure under trial loads that consists of following: definition of the total amount of the load, distribution of the load for each loading phase, definition of the measuring locations, applied sensors and organizational procedures during the testing.

Trial load consisted of available pallets with predetermined weight and it was applied by forklift that is normally used within this warehouse.

For this testing, the total applied weight was 7,25 tons, divided into 2 pallets of 1 ton each, and 7 pallets of 0,75 tons each. This represented an 81% of the maximum load prescribed for the steel rack. The first shelf was loaded with 2,75 tons, Figure 1, what represents 92% of the maximum shelf load (3 tons per shelf). The load on remaining two shelves was 4,5 tons in total, or 2,25 tons per shelf - 75% of the maximum shelf load. Application of higher load levels was limited by the forklift capacity and available pallets.

Testing results showed that load from one shelf has negligible effect on other shelves while the effect on the column is proportional to the total load that was applied.

Testing program consisted of monitoring procedures for overall structural deformations (vertical deflections) and specific deformations within one cross section (strains and rotations).

In total, measurements were taken from 17 locations that were defined in accordance with structural design and expected maximum deformations, Figure 4-6.

Vertical displacements were measured with 5 LVDT sensors. Three of those sensors (U_1, U_2 and U_3) had the accuracy of 1/1000 mm and the maximum displacement capacity of 50 mm. Remaining two displacement sensors had the accuracy of 1/100 mm and displacement capacity of 150 mm ($U_{2'}$ and U_K), Figure 4.

Rotation measurements were conducted by electronic inclinometers at one joint. One inclinometer, K_1, was located on the beam and the other one, K_2, was mounted on the column next to the location of the K_1, Figure 5.

Strain measurements were conducted with 10 strain gauges (S1÷ S10). The strain gauges were manufactured by "Kyowa" (Japan), with the length of 30 mm and nominal resistance of 120Ω, Figure 6.

All measurements were obtained automatically with the data acquisition device.

The testing of one, arbitrarily chosen, steel rack was conducted on October 15, 2018. The loading consisted from 9 loading and 9 unloading phases with the load from the 9^{th} phase being kept on the structure for 4 hours, what is the code demand aimed at determining whether or not there are plastic deformations within the structure.

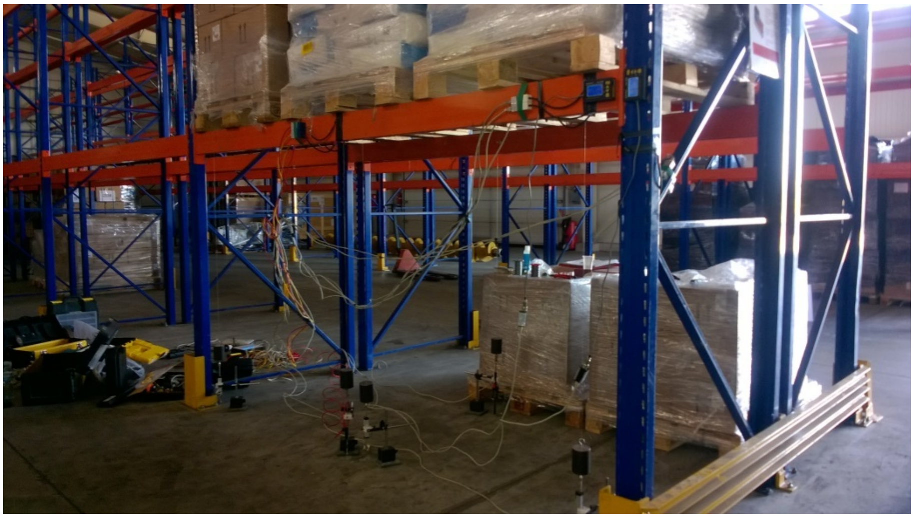

Figure 4. Measurement sensors disposition during testing

Figure 5. Inclinometer located within the beam-to-column connection

Figure 6. Inclinometers and strain gauges located on the horizontal beam during testing

4. TESTING RESULTS

Detailed description of results is given in the Testing report [12] while here the results are given in a shorter form.

Table 1. Measured displacements (with elimination of the end joint displacements)

Load phase	Displacements					Rotations		Load
	x=0	x=L/2 (Beam1)	x=L/2 (Beam2)	x=L/2 (control)	x=L	Beam	Column	
	U_1	U_2	$U_{2'}$	$U_{contr.}$	U_3	K_1	K_2	
	[mm]					[°]		[tons]
0	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.00
1	0.00	5.04	5.04	4.99	0.00	0.058	0.003	1.00
2	0.00	7.70	7.71	7.69	0.00	0.344	0.100	2.00
3	0.00	8.71	8.71	8.65	0.00	0.529	0.127	2.75
4	0.00	8.93	8.94	8.91	0.00	0.578	0.140	3.50
5	0.00	8.98	8.99	8.98	0.00	0.593	0.134	4.25
6	0.00	9.00	9.00	8.98	0.00	0.596	0.117	5.00
7	0.00	9.16	9.18	9.16	0.00	0.598	0.118	5.75
8	0.00	9.17	9.18	9.17	0.00	0.604	0.075	6.50
9	0.00	9.17	9.18	9.16	0.00	0.596	0.056	7.25
0'	0.00	0.16	0.17	0.17	0.00	0.011	0.002	0.00

Table 2. Comparison of calculated and measured stresses - middle of the beam (MPa)

Load phase	Linear calculation - stiff connection				Measurement			
	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	82.59	82.59	-82.59	-82.59	89.59	90.60	-90.42	-90.14
2	106.22	106.22	-106.22	-106.22	124.55	125.95	-125.69	-125.31
3	124.11	124.11	-124.11	-124.11	147.36	149.01	-148.71	-148.26
4	124.41	124.41	-124.41	-124.41	147.77	149.43	-149.12	-148.67
5	124.58	124.58	-124.58	-124.58	148.02	149.68	-149.38	-148.93
6	125.24	125.24	-125.24	-125.24	148.86	150.53	-150.23	-149.77
7	124.26	124.26	-124.26	-124.26	147.54	149.19	-148.89	-148.44
8	122.79	122.79	-122.79	-122.79	145.59	147.22	-146.92	-146.48
9	122.78	122.78	-122.78	-122.78	145.42	147.05	-146.75	-146.31
0'	0.00	0.00	0.00	0.00	2.62	2.46	-2.77	-2.90

Table 3. Comparison of calculated and measured stresses - beam-to-column joint (MPa)

Load phase	Linear calculation - stiff connection				Measurement			
	S_5	S_6	S_7	S_8	S_5	S_6	S_7	S_8
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	70.49	70.49	-70.49	-70.49	61.20	61.52	-61.08	-61.01
2	106.41	106.41	-106.41	-106.41	83.15	83.58	-82.98	-82.89
3	140.00	140.00	-140.00	-140.00	107.35	107.90	-107.13	-107.02
4	138.83	138.83	-138.83	-138.83	106.39	106.94	-106.17	-106.06
5	138.71	138.71	-138.71	-138.71	106.24	106.79	-106.02	-105.91
6	137.57	137.57	-137.57	-137.57	105.31	105.85	-105.10	-104.99
7	136.70	136.70	-136.70	-136.70	104.82	105.36	-104.60	-104.49
8	140.10	140.10	-140.10	-140.10	107.66	108.21	-107.44	-107.33
9	144.83	144.83	-144.83	-144.83	111.47	112.05	-111.25	-111.13
0'	0.00	0.00	0.00	0.00	2.45	2.36	-2.28	-2.32

5. CONCLUSIONS

Based on the conducted testing under trial exploitation load, analysis of the results and comparative analysis with appropriate results from numerical simulation, the following was concluded:

- deformation response of the tested steel rack structure is elastic,
- measured values of the vertical deflections were lower than the ones obtained from the conventional (linear) numerical simulations,
- maximum value of the vertical displacement for exploitation load was $_{max}\delta_{mer}$=9,18 mm. When expressed relative to the span, this value is L/305,
- there were no damages and/or unexpected behavior identified during testing,
- after unloading, permanent displacement was measured at 0,18 mm what is 1,85%, of the measured maximum vertical displacement. This value is within the national code (SRPS U.M1.067) requirements defined for elastic structural behavior without significant permanent deformations.

Having all of the above in mind the test results showed that this structure is capable of reliable exploitation for maximum shelf load of 3000 kg and 9000 kg in total.
However, the testing results revealed that behavior of the steel rack is highly dependant on the stiffness of the beam-to-column connection. In current practice in Serbia, a conventional numerical approach is usually applied in which beam-to-column joint is considered as ideally stiff. As shown in this study (Table 2 and 3), this can lead to underestimation of the stress levels in the middle of the horizontal beam by 20%, while the stresses are overestimated in the joint between the column and the beam by 24%. On one hand this behavior increases the global stability of the columns which have lower stresses as a result of the interaction with the beam, but, on the other hand, this means that the stresses are higher in the middle of the beam, therefore making the structural design possibly unsafe.
Final conclusion is that further testing need to be conducted and more sophisticated, yet practically applicable, beam-to-column numerical simulation need to be applied for structural design of industrial steel racks with heavy loads.

ACKNOWLEDGEMENTS

This paper presents the part of research realized within the project “Improvement of educational process and theoretical and applied research in civil engineering” conducted by the Department of Civil Engineering and Geodesy, Faculty of Technical Sciences, University of Novi Sad.

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ПОНАШАЊЕ ИНДУСТРИЈСКИХ РЕГАЛА ПОД УТИЦАЈЕМ ПРОБНОГ ОПТЕРЕЋЕЊА

Резиме: *Овај рад приказује резултате испитивања индустријског палетног регала под утицајем максималног пробног оптерећења. Резултати испитивања су потврдила да су механичке карактеристике споја стуба и греде унутар палетног регала кључне за понашање регала под утицајем радног оптерећења. Резултати испитивања су показали да конвенционални приступ прорачуну применом линаерних метода са идеализованим везама може довести до погрешних закључака о понашању конструкције и њеном неадеквантом димензионисању.*

Кључне речи: *Индустријски палетни регали, испитивање, пробно оптерећење, понашање конструкције*