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Strength upgrading of existing steel storage rack beam-to-column connections

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ABSTRACT: Steel storage rack systems are intensively used for the safe storage of industrial products. Structural systems employed for storage rack structures are very similar to those employed for conventional steel framed buildings. As in the case of steel frames, main components of rack frames are steel columns interconnected by horizontal steel beams and the resulting frames are laterally stabilized by steel braces. A number of peculiarities that differentiate these systems from conventional steel frames are that all members are thin-walled cold formed steel members, columns have closely spaced perforations along their lengths and the beams are mostly connected to columns by the so-called hooked connections. On the other hand it is one challenging aspect of these structures that their structural system self weight is generally no more than %5 of the total product load they are designed to carry. According to the authors' knowledge, around the world there is a significant number of existing storage rack systems in use by various industry producers. These systems are used for storing heavy products and cover wide spaces on plan and also height. As is the case with conventional building type structures, safe static and seismic design of these structures are of vital importance. Particularly further research is needed to better understand the behavior of the beam-to-column connections under cyclic loading. In this paper it is the authors' intention to focus on the seismic behavior of the hooked beam-to-column connections and investigate possible practical ways to upgrade the strength and energy dissipation characteristics of existing connections.

1   INTRODUCTION

Steel storage rack systems play a key role in the industrial supply chain by providing efficient storage spaces for industrial products. In today's rapidly developing world of manufacturing, the need for storage rack systems is increasing and in addition to the existing number of storage systems a lot more number of systems is being constructed for use by various industry producers.

Considering all the constituent structural elements that make up the structural system, steel storage racks resemble much like the conventional steel braced frames. However, there are a number of peculiarities that differentiate these systems from conventional steel frames. In steel storage rack systems, all members are thin-walled cold formed steel members, columns have closely spaced perforations along their lengths and the beams are mostly connected to columns

by the so-called hooked connections (Figure 1). Therefore compared to the conventional steel frames, all these features of steel storage rack frames result in lightweight, flexible and low-redundancy structural systems.

Figure 1. Constituent structural members of a steel storage rack system

Safe storage of products is of vital importance to prevent both economic and possibly human losses. Among various possible reasons that could risk the safety of the systems, one important reason is the earthquake. The above mentioned flexibility and low-redundancy characteristics of the systems may complicate the behavior of rack frames under lateral seismic effects. In particular the behavior of the hooked beam-to-column connections play an important role in the seismic behavior of these structures (Figure 2). From this viewpoint, in this paper it is the authors' intention to focus on the cyclic behavior of the hooked beam-to-column connections and investigate possible practical ways to upgrade the strength and energy dissipation characteristics of existing hooked connections.

Figure 2. Collapsed rack system in Christchurch earthquake in 2011 (Clifton et al. (2011))

2 EXPERIMENTAL PROGRAM

2.1 Description of the test specimens and the test methodology

An experimental program was carried out on rack beam to column connections with varying beam depths and methods of connections. Table 1 presents a summary of the test program. Two different beam depths and 3 different connection methods were adopted. Column member cross-

sections was kept constant for all tests. Also a constant columns length of 500mm was used and beam lengths were taken as 750mm. In total 6 different tests were carried on rack beam-to-column connections under reversed cyclic loading conditions.

The test apparatus was developed in accordance with RMI 2007 Specification, Section 9.6 as illustrated in Figure 1. The test apparatus with a sample installed can be seen in Figure 2. The rack column and beams are installed in horizontal orientation for maximum support rigidity. Two servo-hydraulic actuators were utilized to apply the rotation and moment at each beam end. The actuators were controlled in displacement mode for equal rotation at each test cycle. The actuator rod displacements were measured by two linear displacement transducers. The applied loads were measured with two 50 kN precision load cells installed between the actuator rod and beam-end clamp fixture. A constant 50 kN axial compression load was applied on the rack column by a hydraulic cylinder during the test. The applied force was maintained by supplying a constant system pressure that was calculated based on the cylinder piston area. Two small hydraulic cylinders were installed on the beam top surface within 50mm from the beam connector. A 5 kN force was applied at each side of the beam simulating pallet loads. The hydraulic pressure was supplied by a pressure reducing valve regulating the pressure at constant 4.15 MPa, so that the applied force would not change when the beams slightly move up and down during the test.

Figure 2. Experimental setup for cyclic testing of beam-to-column connections

Table 1. Summary of the test program

Sample ID	Beam section	Method of connection
WB100.40.NP	Box 100.40.2mm	Hooked
WB100.40.2P	Box 100.40.2mm	2 pins added on both sides
WB100.40.4P	Box 100.40.2mm	4 pins added on both sides
WB140.40.NP	Box 140.40.2mm	Hooked
WB140.40.2P	Box 140.40.2mm	2 pins added on both sides
WB140.40.4P	Box 140.40.2mm	4 pins added on both sides

As also shown in Figure 3, two different beam cross-section depths were tested with three different connection types. Typically, in practice, rack beams are connected to the perforated rack columns by the hooked connection shown in the middle photograph of Figure 3. In this study, a new practical idea is tested as a means to upgrade the performance of hooked connections under reversed cyclic effects. As can be seen in the hooked connection, in the fabrication stage small bolt holes were provided under every hook. Normally, these holes are used to insert a so called "safety pin" to prevent possible uplift of the beam due to an accidental hitting of a forklift truck. In this study, this application is taken a step forward such that more pins (or bolts) are used so as to provide possible structural upgrade. The selected specimens included four hooks and four bolt holes and hence these holes were used to make additional connections with 2 and 4 bolts along the connection. The case of adding 4 additional bolts on both sides of the connection is shown in Figure 3. So in addition to the hooked connection, 4 bolts were applied on both sides. The designation for this specimen is WB140.40.4P and refers to a Welded Beam of cross-section Box 140.40 and connected by hooks and additional 4 bolts or Pins (4P) on both left and right connections. Cyclic loading protocol recommended in the relevant chapter of the current Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks (ANSI MH16.1:2012) document was used. Section 9.4 of the ANSI MH16.1:2012 Specification presents a testing protocol intended to evaluate the characteristics of typical rack beam-to-column connections.Table 2 presents the details of the loading sequence. The tests were conducted by controlling the peak Drift Angle, θ, imposed on the Test Specimen. For a load application point at 600mm from the column side along the beam length corresponding beam end displacement values are as given in Table 2.
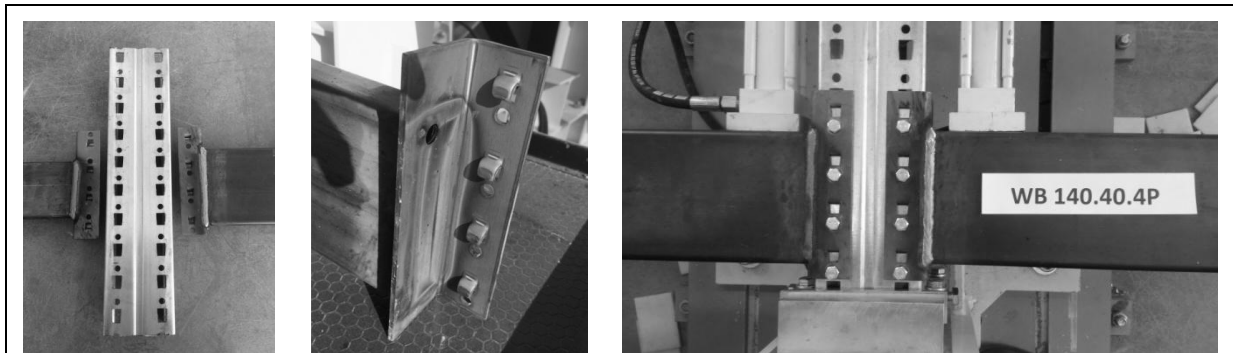

Figure 3. Hooked and hooked & bolted connections

Table 2. Loading Sequence for Storage-Rack Beam-to-Column Connections to ANSI MH16.1:2012
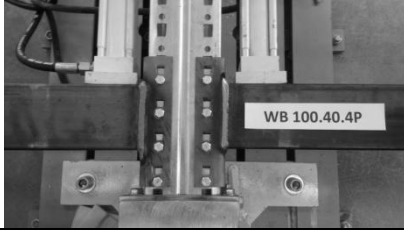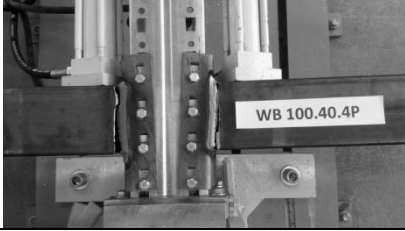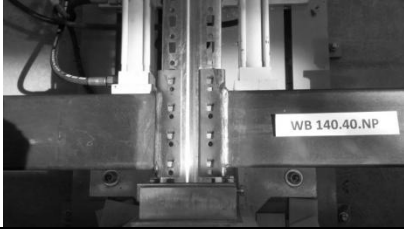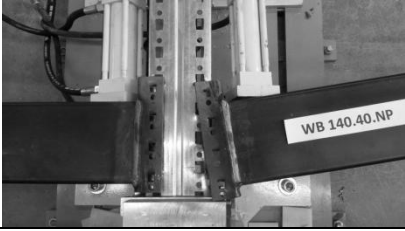
| Test Stage	Number of Cycles	Beam End Displacement (mm)
1	3 cycles at θ = 0.025 radians	15,25
2	3 cycles at θ = 0.050 radians	30,53
3	3 cycles at θ = 0.075 radians	45,84
4	3 cycles at θ = 0.100 radians	61,20
5	2 cycles at θ = 0.150 radians	92,19

2.2 Test Results

2.2.1 Cyclic behavior of the connections

Table 3 presents photographs of all the specimens before loading and right after failure. As expected for the NP (No Pin but only hooked) connections, failure occurred simply by shearing off the hooks. On the other hand, for connections with additional bolts (2P or 4P), failure was either accumulating over the beam end welds or the column web depending on the stiffness of the beam. For the 100mm depth beams, both for 2P and 4P cases, failure occurred by tension rupturing of the welds. For the stiffer 140mm depth beams, welds were stronger and the failure behavior was governed by a combination of column web buckling and localized rupture failure of the column material around bolt holes and hook perforations.

Table 3 Collapse behavior of the tested connections

Sample ID	Before loading	After failure
WB100.40.NP		
WB100.40.2P		
WB100.40.4P		
WB140.40.NP		

WB140.40.2P

WB140.40.4P
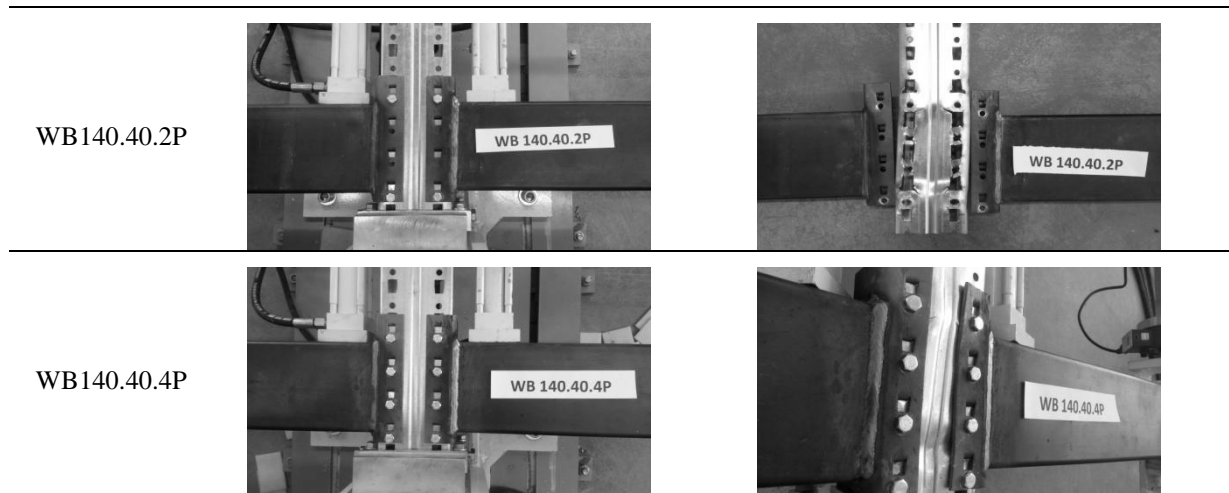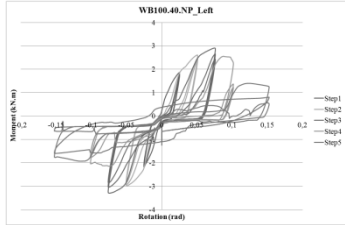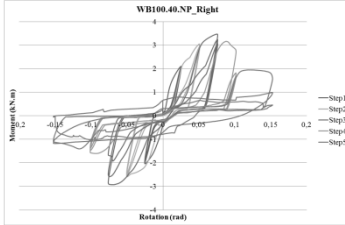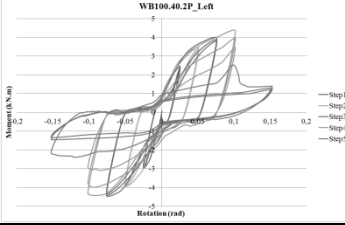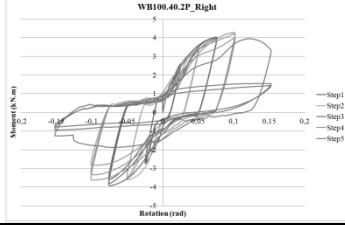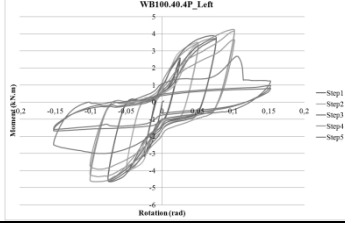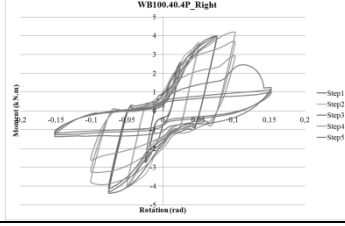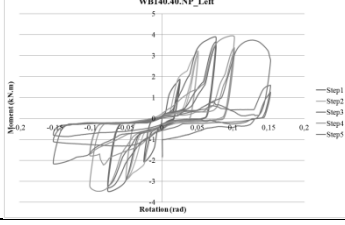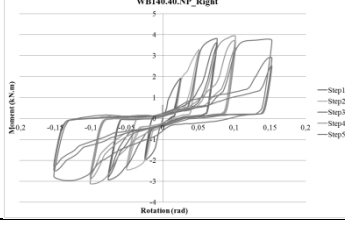
2.2.2 Comparison of the test results

In Table 4, peak moment values achieved by left and right beam connections are given. These values are maximum values obtained throughout the test history that includes all 5 cycles. Rotations corresponding to maximum moments were achieved mostly between 3rd and 4th cycles after which failure started and they va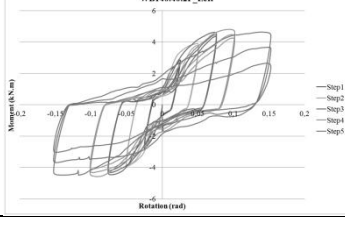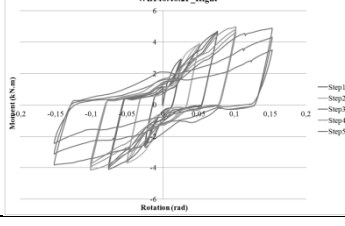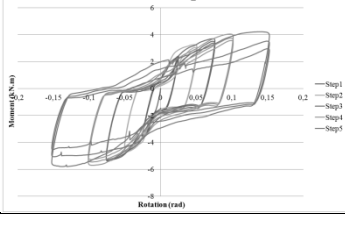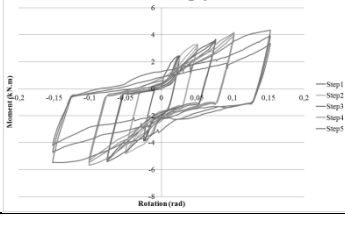ried between 0,075 and 0,100 radians. In the last two columns of Table 4, average values of clockwise and anti-clockwise (positive and negative) moments of left and right beam connections are presented. Comparing NP samples with 2P and 4P samples, change in achieved peak moments ranges between 26% and 47%. Therefore, the contribution of adding 2 or 4 bolts into an existing hooked connection is significant in terms of maximum moment resistance. Comparing 2P and 4P samples among themselves, change in peak moment values is not as noticeable ranging between 1% and 9% and as expected favoring the 4P cases. Moment-rotation curves are presented in Table 5 for left and right beam connections for each sample considered. In general, for a specific sample, left and right connections exhibit very similar moment-rotation characteristics.

Table 4 Peak moment values for left and right beam connections

Sample ID	Left beam		Right beam		Whole joint	
	Clockwise (CW) Moment	Anti-clockwise (ACW) Moment	Clockwise (CW) Moment	Anti-clockwise (ACW) Moment	Average CW Moment	Average ACW Moment
WB100.40.NP	2,9100	3,3042	2,9244	3,4692	2,9172	3,3867
WB100.40.2P	4,3986	4,4712	3,9336	4,2882	4,1661	4,3797
WB100.40.4P	4,2510	4,6524	4,3824	4,1946	4,3167	4,4235
WB140.40.NP	3,9432	3,5034	3,1344	3,9498	3,5388	3,7266
WB140.40.2P	4,8066	4,5810	4,1520	4,9656	4,4793	4,7733
WB140.40.4P	4,2162	5,8044	5,6904	4,3428	4,9533	5,0736

Table 5 Full moment-rotation curves for left and right beam connections for the tested specimens

Sample ID	Left connection	Right connection
WB100.40.NP		
WB.100.40.2P		
WB100.40.4P		
WB140.40.NP		
WB140.40.2P		
WB140.40.4P		

A noticeable improvement in cyclic behavior is noted for the upgraded connections achieved by the introduction of additional bolts (2P and 4P). Also, a more stable hysteretic behavior is observed for these connections evidenced by less "pinched" hysteretic behavior which is more observed for the hooked (NP) connections. Variation of stiffness in 5 successive loading steps during cyclic loading was cakculated for the WB140.40 beam connections with three different connection types (NP, 2P and 4P). It is observed that in the first cycle, the stiffness is the greatest for the 4P connection and it is the smallest for the NP (hooked only) connection. The difference between these stiffness values (for 4P and NP) is calculated as around 82%. For the 2P connection, the initial stiffness is around 33% greater than that for the NP connection. At the end of the last cycle (5th) the differences in stiffness values for the three connection types seem to become less pronounced. However, it should be stated that behavior after the 3rd cycle is not of practical significance in terms of connection stiffness as failure of the specimens were generally observed to occur after the 3rd cycle. Using the cyclic curves presented in Table 5, total accumulated energy levels at the end of the 5th cycle was calculated for each of the above mentioned specimens. The total accumulated energy for the 4P connection specimen is calculated as 8495 kN.mm, for the 2P specimen around 7145 kN.mm and this drops down to 2472 kN.mm for the NP specimen. Therefore both in terms of stiffness and total accumulated energy levels, significant differences are achieved by the introduction of additional bolts.

3   CONCLUSIONS

In this study, the cyclic behavior of hooked connections of storage rack systems was experimentally investigated and further tests were carried on the connections structurally upgraded by simple introductions of bolts. Tests were carried out on connections formed by two different beam sections and three different connection methods. In the study, the hooked connections, that are widely used in practice, were essentially benchmarked against a proposed connection method involving the introduction of extra bolts. The proposed method can be considered as a way of structurally upgrading an existing hooked beam-to-column connection. The test results revealed the significant improvement in cyclic behavior for the upgraded specimens. Initial stiffness values greater than up to 82% of the hooked-only connections were achieved. On the other hand, total accumulated energy calculated over the hysteretic curves were found to be around 4 times greater for the bolted cases compared with the unbolted hooked cases. Peak moments achieved for the upgraded connections were also up to 47% greater. In general, the proposed method of upgrading appears to be a very effective way of increasing the seismic performance of existing hooked connections.

4   REFERENCES

Clifton C, Bruneau, M, MacRae G, Leon, R and Fussell, A. 2011, Steel Structures Damage From The Christchurch Earthquake Series Of 2010 and 2011, *Bulletin of The New Zealand Society for Earthquake Engineering,* 44(4): 297-318.

ANSI MH16.1:2012. Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks, Rack Manufacturers Institute (RMI)

5   ACKNOWLEDGEMENTS