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Strength upgrading of steel storage rack frames in the down-aisle direction

Bassel El Kadi [*1], Cumhur Coşgun [2], Atakan Mangır [1] and Güven Kıymaz [3]

[1] *Department of Civil Engineering, Istanbul University, Avcilar Campus, 34320, Istanbul, Turkey*
[2] *Wichita State University, College of Engineering, 67260, Kansas, USA*
[3] *Antalya International University, Universite Cad. No:2, Dosemealti, 07190, Antalya, Turkey*

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Abstract. This paper focuses on the seismic performance of pallet-type steel storage rack structures in their down aisle direction. As evidenced by experimental research, the seismic response of storage racks in the down-aisle direction is strongly affected by the nonlinear moment-rotation response of the beam-to-column connections. In their down-aisle direction, rack structures are designed to resist lateral seismic loads with typical moment frames utilizing proprietary beam-to-column moment-resisting connections. These connections are mostly boltless hooked type connections and they exhibit significantly large rotations resulting in large lateral frame displacements when subjected to strong ground motions. In this paper, typical hooked boltless beam-to-column connections are studied experimentally to obtain their non-linear reversed cyclic moment-rotation response. Additionally, a compound type connection involving the standard hooks and additional bolts were also tested under similar conditions. The simple introduction of the additional bolts within the hooked connection is considered to be a practical way of structural upgrade in the connection. The experimentally evaluated characteristics of the connections are compared in terms of some important performance indicators such as maximum moment and rotation capacity, change in stiffness and accumulated energy levels within the cyclic loading protocol. Finally, the obtained characteristics were used to carry out seismic performance assessment of rack frames incorporating the tested beam-to-column connections. The assessment involves a displacement based approach that utilizes a simple analytical model that captures the seismic behavior of racks in their down-aisle direction. The results of the study indicate that the proposed method of upgrading appears to be a very practical and effective way of increasing the seismic performance of hooked connections and hence the rack frames in their down-aisle direction.

Keywords: steel storage rack; hooked connection; cyclic test; seismic performance; structural upgrade

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 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 (Fig. 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.

Safe storage of products is of vital importance to prevent both economic and possible human life 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

Fig. 1 Typical hooked beam-to-column connection in storage rack frames

∗Corresponding author, Ph.D. Student,
E-mail: bassel_elkadi@hotmail.com

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

behavior of the hooked beam-to-column connections plays an important role in the seismic behavior of these structures (Fig. 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. An experimental program was carried out to study typical hooked beam-to-column connections to obtain their non-linear reversed cyclic moment-rotation response. Additionally, a compound type connection involving the standard hooks and additional bolts were also tested under similar conditions. The simple introduction of the additional bolts within the hooked connection is considered to be a practical way of structural upgrade in the connection. The experimentally evaluated characteristics of the connections are compared in terms of some important performance indicators such as maximum moment and rotation capacity, change in stiffness and accumulated energy levels within the cyclic loading protocol. Finally, the obtained characteristics were used to carry out seismic performance assessment of rack frames composed of the tested beam-to-column connections. The assessment involves a displacement based approach that utilizes a simple analytical model that captures the seismic behavior of racks in their down-aisle direction.

Experimental and analytical studies related to the seismic performance of storage racks are limited to warrant a satisfactory basis for seismic design of these systems. On the other hand, due to the great number of types of beam-to-column connectors used in practice as well as the different geometries employed for rack beam and column members, design approaches to evaluate the seismic performance of rack frames are not completely available. Therefore, to understand the seismic behavior of storage rack systems and to fill the gap in design a number of experimental and analytical studies have been carried out. Saravanan *et al*. (2014) studied the dynamic characteristics of a 3-D single bay two storey pallet rack system with hook-in end connectors by shake table testing. An attempt was made to evaluate the realistic dynamic characteristics by using Finite Element Analysis modeling of the tested system. The stiffness values used in modeling of the hook-in connector were taken from a previous study by Prabha *et al*. (2010). The results from modal analysis were in good agreement with the respective experimental results. Kalavagunta *et al*. (2012) investigated the progressive collapse of cold formed storage rack structures subjected to seismic loading, using pushover analysis. A simple storage rack cold formed steel structure was analyzed by using non-linear static procedure in accordance with FEMA 356 specifications. The procedure was found to be a useful analysis tool for the conventional storage racking systems giving good estimates of the overall displacement demands, base shears and plastic hinge formation. Petrovic and Kilar (2012) examined the seismic response of an existing externally braced steel frame high-rack structure and analyzed the effects of mass eccentricities that can be realistically achieved by asymmetric positioning of the stored payload. The seismic performance was analyzed by using unidirectional non-linear dynamic analyses as well as by non-linear static analyses. The results showed that most unfavorable payload eccentricities might increase the seismic risk leading to local instability of the rack columns. In the research study by Sideris *et al*. (2010), the seismic behavior of palletized merchandise stored on shelves of pallet-type steel storage racks was investigated and the concept of incorporating slightly inclined shelving was proposed as a measure for mitigating merchandise shedding. Pull tests and shake table tests were conducted. The major objective of the shake table tests was to characterize the dynamic response of the palletized merchandise under earthquake excitation imposed at the base of rack structures, and determine experimentally the pallet shedding fragility under an ensemble of ground excitations. From the results of the shake table tests, the concept of inclined shelving was shown to be very effective. Bajoria *et al*. (2010) studied the seismic response of pallet rack structures through three dimensional finite element modeling of pallet rack frames with semi-rigid connections. Stiffness values for the connections were obtained by carrying out conventional cantilever tests on typical rack beam-to-column connections. From the experimental study on connections and finite element modal analysis, a simple analytical model that captures the seismic behavior of storage racks in their down aisle direction was proposed.

Besides the aforementioned latest research on seismic behavior of storage rack systems a number of valuable earlier studies should also be mentioned. Shake table tests were carried out by various researchers both in Europe and the USA.

Two full-scale shake-table testing investigations of storage racks fully loaded have been performed in Europe (Castiglioni *et al*. 2003) and other three in the United States (Chen *et al*. 1980, 1981); Filiatrault and Wanitkorkul 2004). Shake table tests on different types of rack systems were carried out on both down-aisle and cross-aisle directions. The test results indicated that the rotational stiffness of beam-to-column connections is the main factor influencing the down-aisle seismic response of pallet racks. Bernuzzi and Castiglioni (2006) performed a series of 11 monotonic and 11 cyclic tests on two different types of beam-to-column connections used in Europe. The maximum rotation achieved was way beyond practical design values. The results of the cyclic tests exhibited, with increasing number of response cycles, pronounced pinching behavior associated with slippage and plastic deformations of the connectors leading to significant reduction of energy dissipation capacity. Quasi-static testing was conducted on 22 different types of interior beam-to-upright subassemblies by Filiatrault *et al*. (2006b). The test data indicated that beam-to-column connections exhibit very ductile and stable behavior, with rotational capacities beyond the values observed during shake-table tests and expected from a design seismic event.

In general, findings with regards to the behavior of beam-to-column connections in the down aisle direction revealed that the seismic response of storage racks in the down-aisle direction is strongly affected by the nonlinear moment-rotation response of the beam-to-column connections.

2. Experimental program

2.1 Description of the test specimens and the test methodolozgy

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 (100 mm and 140 mm box sections) and 3 different connection methods were adopted. Detailed description of the connection methods is given below. Column member cross-section was kept constant for all tests. Also a constant column length of 500 mm was used and beam lengths were taken as 750 mm. 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 2012 Specification (ANSI MH16.1 2012: Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks, Rack Manufacturers Institute (RMI)), Section 9.6. The test apparatus with a sample installed can be seen in Fig. 3. 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 50 mm 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 600 psi, so that the applied force would not change when the beams slightly move up and down during the test.

Two different beam cross-section depths were tested with three different connection types. As previously mentioned, typically, in practice, rack beams are connected to the perforated rack columns by the so called hooked connections (Fig. 1). Also note that the beam is welded to a steel angle section (usually called a “connector”) on which the hooks are located. In this study, a simple practical idea is tested as a means to upgrade the performance of hooked connections under reversed cyclic effects. As shown in Fig. 1, in the fabrication stage closely spaced circular holes are provided along the column web. Typically, 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 similar size bolts (rather than unthreaded pins) are used so as to provide a degree of structural upgrade. In the experimental work, the chosen specimens included four hooks and at most four bolt holes available to connect the beam end connector element onto the column web. Hence it was decided to provide the hooked connections with 2 and 4

Table 1 Summary of the test program

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

Fig. 3 Experimental setup for cyclic testing of rack beam-to-column connections

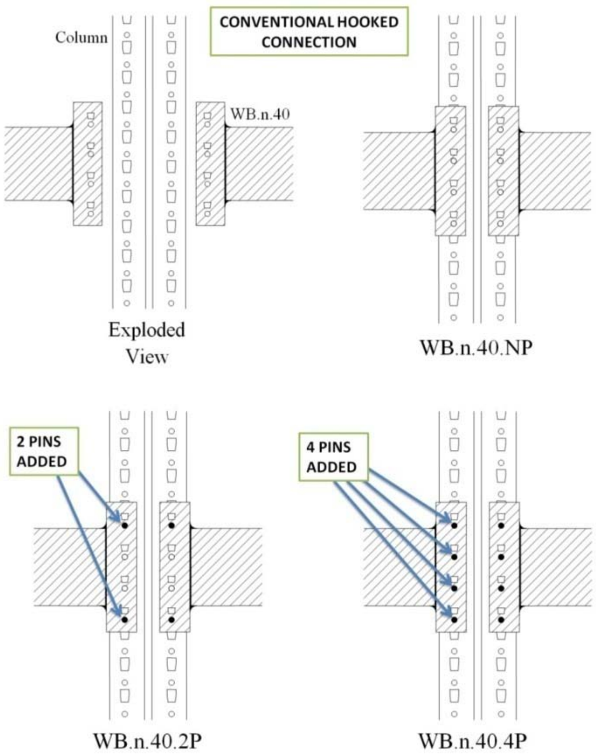


Fig. 4 Schematic description of the test specimens

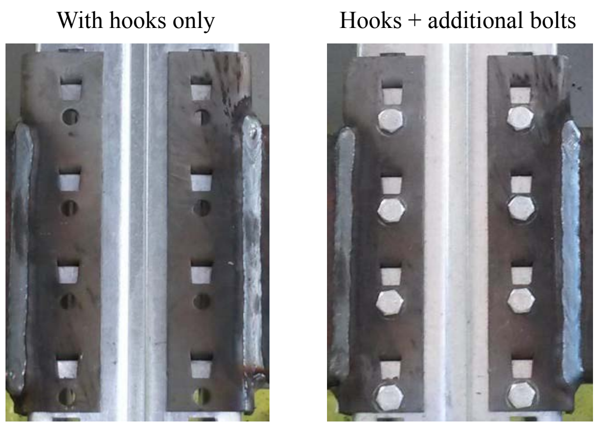


Fig. 5 Specimen with and without additional bolts (pins)

additional threaded bolts on both sides of the column. Schematic description of the test specimens produced in this fashion is presented in Fig. 4. Also in Fig. 5, connections with hooks only and hooks and additional bolts are compared for the 4 bolt case. The designation for this specimen in Fig. 5 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. In Table 1, specimen designations were given in this format e.g. 2P referring to 2 additional bolts and NP referring to no bolts i.e., only hooked.

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

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

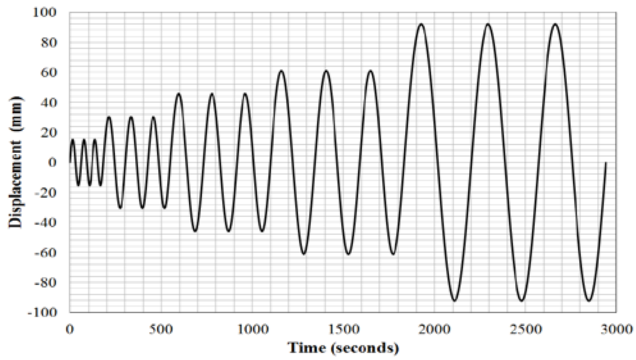


Fig. 6 Cyclic loading curve used in the experimental study

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 whereas Fig. 6 presents the corresponding loading curve. The tests were conducted by controlling the peak Drift Angle, θ, imposed on the Test Specimen. For a load application point at 600 mm from the column side along the beam length corresponding beam end displacement values are as given in Table 2.

2.2 *Test Results*

2.1.1 *Cyclic behavior of the connections*

Tables 3A and 3B present 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 (the weakest link). 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 100 mm depth beams, both for 2P and 4P cases, failure occurred by tension rupturing of the welds. For the stiffer 140 mm 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.

2.1.2 *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

Table 3A Collapse behavior of the tested connections (100 mm depth beam connections)

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

Table 3B Collapse behavior of the tested connections (140 mm depth beam connections)

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

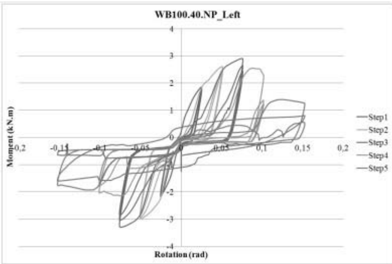
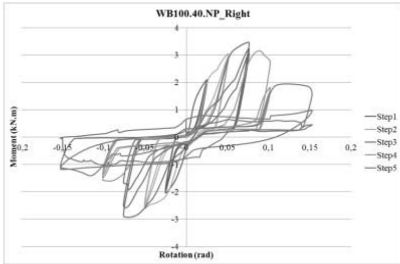
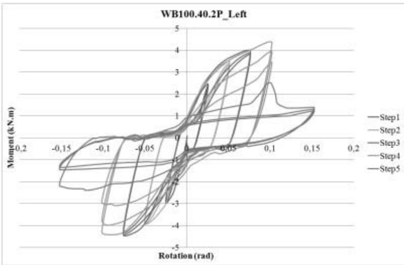
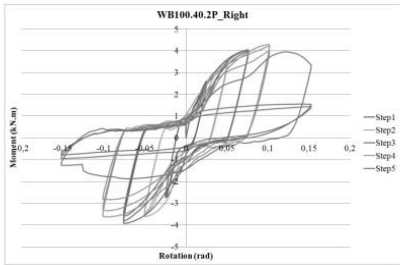
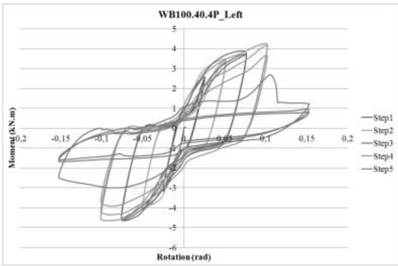
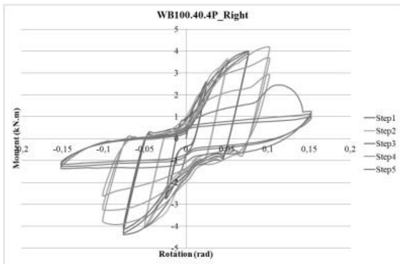
moments were achieved mostly between 3rd and 4th cycles after which failure started and they varied between 0,075 and 0,100 radians. In the last two columns of Table 4, average values of clockwise and anti-clockwise (positive and negative) moments of left and right beam connections are presented. Comparing 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 Tables 5a-5b 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. 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

Table 4 Peak moment values for left and right beam connections

	Left beam		Right beam		Whole joint	
Sample ID	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 5A Full moment-rotation curves for left and right beam connections for the tested specimens (100 mm depth beam connections)

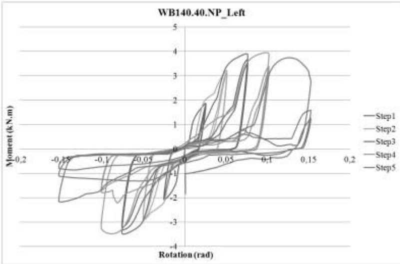
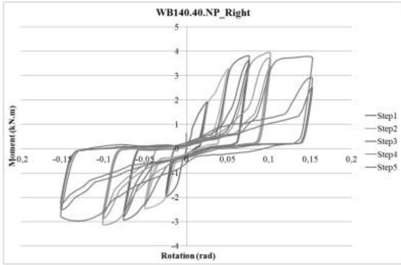
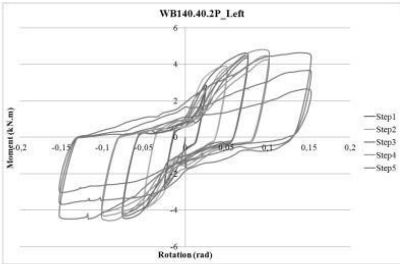
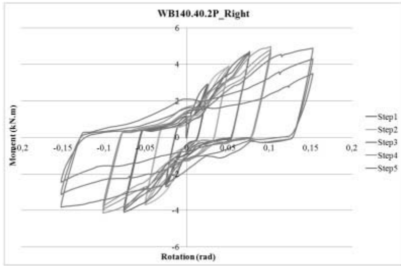
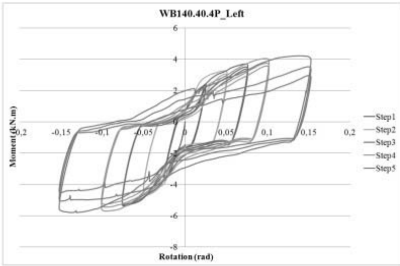
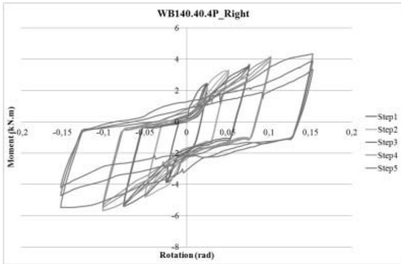
Sample ID	Left connection	Right connection
WB100.40.NP		
WB.100.40.2P		
WB100.40.4P		

stable hysteretic behavior is observed for these connections evidenced by less “pinched” hysteretic behavior which is more observed for the hooked (NP) connections. In general, comparing the average maximum moment values (M_{max}) achieved by both the 100 mm and 140 mm depth beam connections it is noted that relatively greater maximum moment values were achieved for 140 m depth specimens and at relatively greater values of corresponding rotation values (θ_{max}).

In Fig. 7, variation of stiffness in 5 successive loading steps during cyclic loading is given 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

Table 5B Full moment-rotation curves for left and right beam connections for the tested specimens (140 mm depth beam connections)

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

NP specimen.

Therefore, both in terms of stiffness and total accumulated energy levels, significant differences are achieved by the introduction of additional bolts.

3. Seismic performance assessment

Seismic performance assessment of typical rack frames was carried out for frames composed of connections tested within this study. The assessment mainly focuses on determining the efficiency of the proposed structural upgrading method. For this purpose, a simple displacement-based seismic design procedure proposed by Filiatrault *et al*. (2006a) was used. The procedure mainly aims to verify the collapse prevention of storage racks in their down-aisle direction under MCE (Maximum Credible Earthquake) ground motions. It is based on a simple analytical model that captures the seismic behavior of racks in their down-aisle direction. The model assumes that the beams and columns remain elastic in the down-aisle direction and that all nonlinear behavior occurs in the beam-to-column connections and the moment-resisting connections between the base columns and support concrete slab. Therefore, the behavior is based on the effective rotational stiffnesses developed by the beam-to- column connectors and column-to-slab connections that vary significantly with connection rotation (Filiatrault *et al*. 2006a).

A summary of the steps involved in the assessment method is given below. The description of the parameters involved is given separately in Table 6.

(1) The fundamental period (T_1) is calculated as a function experimentally obtained connection stiffness, $k_c = \frac{M_{max}}{\theta_{max}}$, where M_{max} and θ_{max} are experimental maximum values for connection moment and rotation, respectively.

$$T_1 = 2\pi \sqrt{\frac{\sum_{i=1}^{N_L} W_{pi} h_{pi}^2}{g\left(N_c\left(\frac{k_c k_{be}}{k_c+k_{be}}\right) + N_b\left(\frac{k_b k_{ce}}{k_b+k_{ce}}\right)\right)}}$$

(2) The maximum displacement demand D_{max} by adjusting the first-order displacement demand D to account for second-order P-delta effects is calculated

$$D_{max} = D(1+\alpha)$$

$$D = \frac{g S_{M1} T_1}{4\pi^2 B}$$

$$1+\alpha = 1 + \frac{\sum_{i=1}^{N_L} W_{pi} h_{pi}\left(\frac{k_c+k_{be}}{k_c k_{be}}\right)}{\left(N_c + N_b\left(\frac{k_b k_{ce}}{k_c k_{be}}\right)\left(\frac{k_c+k_{be}}{k_b+k_{ce}}\right)\right)}$$

(3) The maximum rotational demand in the connectors (θ_{demand}) is calculated

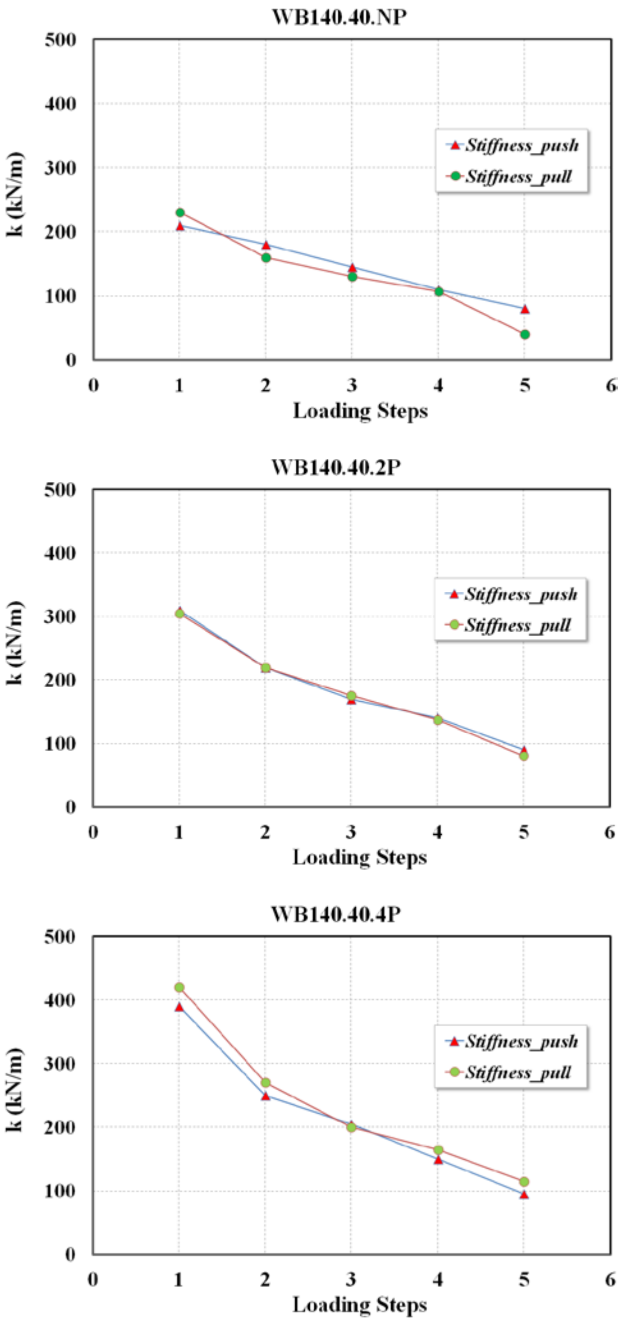


Fig. 7 Change in stiffness with loading steps during cyclic loading

$$\theta_{demand} = \frac{D_{max}}{0.72 h_{tot}}$$

(4) If the rotational demand (θ_{demand}) is less than maximum rotational capacity, (θ_{max}) the connection design is adequate to prevent the collapse of the rack under the MCE.

A case study problem was solved using the above equations for a four bay, three storey rack frame. Table 6 presents the descriptions, input and calculated values for the parameters involved in this example frame including 140.40.2P type connections.

Four bay-three storey rack frames with constant width

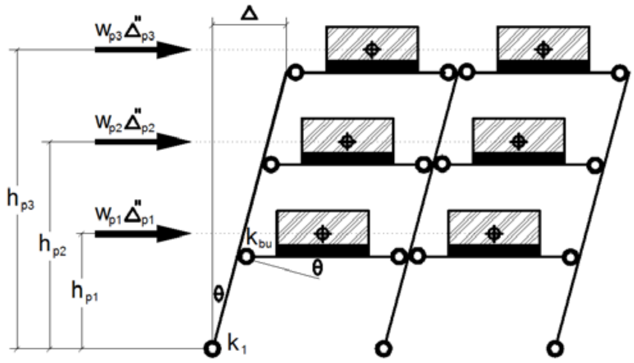


Fig. 8 Analytical model used for the seismic performance assessment of down-aisle frame behavior (Filiatrault *et al*. 2006a)

Table 6 Input and calculated values for a four bay, three storey rack frame

Pallet weight	W_{pi}	=	15	(kN)
Pallet height	P_h	=	0	(m)
Clear span of beams	L	=	2.67	(m)
Clear height of upright	H	=	1.52	(m)
Number of bays	N_{bay}	=	4	
Number of levels	N_L	=	3	
Number of beam to upright connection	N_c	=	48	
Number of base plate connections	N_b	=	10	
Youngs modulus	E	=	200000000	(kN/m^2)
Beam inertia	I_b	=	0.0000016	(m^4)
Upright inertia	I_c	=	3.2441E-07	(m^4)
Beam end rotational stiffness	k_{be}	=	719.1011236	(kN.m/rad)
Upright end rotational stiffness	k_{ce}	=	170.7421053	(kN.m/rad)
One-second MCE accelartion	S_{M1}	=	1	(g)
Damping coefficient	B	=	1.7	
Minimum permitted connection stiffness	k_c	=	59.63	(kN.m/rad)
Minimum permitted base plate stiffness	k_b	=	59.63	(kN.m/rad)
Maximum rotation capacity	$\theta_{\max}$	=	0.120	(radians)

and height dimensions (as given in Table 6), constant pallet weight value but with different connection types (Table 1) were analyzed in this fashion to evaluate collapse prevention in the down-aisle direction under the MCE ground motions. Using the aforementioned equations, rotational demand, θ_{demand}, values were calculated and compared with the experimentally achieved rotation capacity, θ_{max}, values for the above described rack frames.

Table 7 Seismic performance assessment of rack frames with different connection configurations

Connection type (Table 1)	T_1	D	$D_{\max}$	θ_{demand}		$\theta_{\max}$	Assesment result
100.40.**NP**	1.982	0.289	0.369	0.112	>	0.071	Frame inadequate
100.40.**2P**	1.773	0.259	0.316	0.096	>	0.085	Frame inadequate
100.40.**4P**	1.686	0.246	0.295	0.092	>	0.088	Frame inadequate
140.40.**NP**	1.908	0.279	0.350	0.107	>	0.089	Frame inadequate
140.40.**2P**	1.716	0.251	0.303	0.092	<	0.132	Frame adequate
140.40.**4P**	1.591	0.233	0.274	0.083	<	0.150	Frame adequate

Table 7 presents the results for the seismic performance assessment of the frames with different connection configurations as described in Table 1. In line with the procedure described above, experimentally obtained connection stiffness values were used to calculate the fundamental period (T_1) of the frames. The greatest period value was calculated for the frame with **100**.40.**NP** connections and the smallest value for the frame with **140**.40.**4P** connections which, in this study, represent the weakest and strongest connections, respectively. As expected, for a constant beam depth (100 mm or 140 mm) introduction of additional bolts (2P and 4P) leads to reductions in the fundamental period of the frames. Based on the T_1 values maximum frame displacement demand values (D_{max}) were calculated for all the frames for constant ground acceleration and damping coefficient. And finally connection rotational demand (θ_{demand}) values were compared with experimentally obtained maximum rotational capacity (θ_{max}) values for all the frames with different connection configurations. For the 100 mm depth beam connections the assessment results show that in all three cases of connections with hooks and with additional bolts, maximum connection rotational capacities are all smaller than the rotational demand resulting in collapse of the rack frames under the MCE. On the other hand for the 140 mm depth connections, the frames with hooked-only connections are found to be inadequate whereas with the introduction of the bolts (both 2 and 4 bolts) collapse was prevented under the MCE.

Collapse prevention was not possible for the 100 mm depth beam connections even with the introduction of additional bolts. This is mainly due to the fact that, as observed in the test and also shown in Table 3, welds between the beam and the connecter angle failed before the bolts could be activated. Hence the contribution of the additional bolts to the maximum rotational capacity was limited. On the other hand no weld failures were observed for the 140 mm depth beams and additional bolts in both 2P and 4P connections were significantly contributing to the connection rotational capacity leading to collapse prevention of the rack frames incorporating such upgraded connections.

4. Conclusions

Storage rack systems are of vital importance in our modern industrial world. They play a key role in the logistics supply chain of products. Considering the possible economic and human life losses, the seismic safety of these systems is critical. Particularly rack systems directly accessible to public and used in big box stores should not pose any risk during a strong ground shaking. Rack systems are structural load carrying systems typically made up of cold formed steel elements assembled in a similar way conventional steel framed structures are assembled. Nevertheless, columns, beams, braces and connections with characteristics peculiar to these systems necessitate a different treatment in their structural design. For example, the hooked beam-to-column connections results in a markedly semi-rigid behavior. On the other hand, under strong ground motions, storage rack frames have their inelastic behavior occur directly in the semi- rigid beam-to-column connections and hence the connection behavior plays a significant role in the frame behavior. In this study, the cyclic behavior of such connections was experimentally investigated and further tests were carried on the connections structurally upgraded by simple introduction 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, which are widely used in practice, were essentially bench-marked against a proposed connection method involving the introduction of extra bolts. The proposed method can be considered as a practical 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.
- The 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.
- To evaluate whether a rack frame will likely not collapse in the down-aisle direction under the maximum credible earthquake a simple displacement based procedure was used for frames incorporating the tested beam-to-column connections. Promising results were obtained for frames with upgraded connections and beam depths of 140 mm. Collapse prevention under the maximum credible earthquake was achieved for these frames which would otherwise collapse under the same ground motion if

no structural upgrading was provided.

- The study indicates that the proposed method of upgrading appears to be a very practical and effective way of increasing the seismic performance of existing hooked connections and hence the existing rack frames in their down-aisle direction.

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