EXPERIMENTAL ANALYSIS OF BEAM-TO-COLUMN CONNECTION IN STEEL STORAGE RACKS USING CANTILEVER TEST AND PORTAL TEST METHOD

N. ASAWASONGKRAM[1*†], P. CHOMCHUEN[1], and P. PREMTHAMKORN[1]

[1]*Faculty of Engineering, Mahanakorn University of Technology, Thailand*

ABSTRACT

This paper presents experimental results of a typical steel storage rack beam-to-column connection, which steel tabs welded at the end of the beam are engaged into the perforated column. The beam-to column connections are tested using the cantilever test and the portal test method according to the international racking design specification. Four different levels of vertical service loadings are conducted for the portal test. The results from a pushover analysis of a single story frame using a moment-rotation relation of beam-to-column connections obtained from cantilever tests are compared with the experimental results from portal tests. The analytical results show a good correlation with the experimental results from the portal test for no vertical loadings and medium vertical loadings. For high vertical loadings and very high vertical loadings, the analytical results do not produce a good correlation with the experimental results from the portal test. The cantilever test cannot represent the effect of the presence of the vertical service loading in actual field. These effects increase the initial stiffness and decrease the strength of the connection comparing with the results from the cantilever test and lead to a non-correlation of the analytical results compared to the test results from portal tests for a high and very high vertical loading.

Keywords: Cantilever tests, Connection, Moment-rotation, Portal tests, Steel storage racks.

1. INTRODUCTION

In recent years, steel storage racks are extensively used in industry and large public warehouse for storing products. This type of structure has become a common feature in several countries. The main components of the structure are box beams, beam end connectors, and perforated thin wall cold-formed open sections columns. The beam connects to the column by the steel tabs inserted into the perforated column. According to the previous experimental study, this type of connections can be classified as a semi-rigid connection with a low to moderate strength and stiffness (Bernuzzi and Castiglioni 2001, Bajoria and Talikoti 2006, Prabha et al. 2010). Generally the storage racks are not braced in the longitudinal due to the continuously accessible to the product in service. Such a

* Corresponding author: Email: nattawutcivil@gmail.com

† Presenter: Email: nattawutcivil@gmail.com

configuration makes the longitudinal direction particularly critical under a lateral excitation. The lateral behavior of the storage rack in the longitudinal direction depends significantly on the behavior of the beam-to-column connections. Therefore, it is important to have proper method of determining it. For beam-to-column connections, there are a great difference exist in member geometry and connection systems (Markazi et al. 1997), all international standards for steel storage rack (AS 1993; RMI 2008; FEM 1998) require specific test to determine the reliable of moment-rotation relation of beam-to-column connection. Two tests to determine the connection behaviors are: the cantilever test and the portal test.

In the cantilever test a short length of beam is connected to a column and then load to failure. Many researchers have performed the cantilever test method (Markazi et al. 1997; Bernuzzi and Castiglioni 2001; Bajoria and Talikoti 2006). Although the cantilever test provides a simple method of determining the connection strength and stiffness, the disadvantage of this method is the effect of the vertical service loading cannot represent. In order to better represent the effect of vertical service loading in a beam-to-column connection, the portal test method has been considered. In this testing method, the beam is connected to two columns to form a portal frame. Both ends of the column shall be pinned at its base. The vertical load shall be applied to the pallet beam to simulate the usual service loading. Then a lateral load is applied on the column at the level of the beam. Although the portal test can represent the behavior of racks in actual condition, quite a few numbers of portal test have been reported (Krawinkler et al. 1979; Harris 2006) due to it is rather difficult to perform.

This paper presents experimental results of the cantilever tests and the portal tests on the behavior of beam-to-column connection of steel storage rack. The portal tests are performed with various vertical loading levels. The effects of vertical loading on the moment-rotation relation of beam-to-column connection are described. An analysis of a single story frame with moment-rotation of connections obtained by a cantilever test is compared with the experimental results from portal test. The correlations between such the two tests are discussed.

2. EXPERIMENTAL INVESTIGATIONS

The test specimens are selected from a commercial Thailand manufacture. The geometry of the specimens is depicted in Figure 1. These values are given as an average value of the several measurements from each series.

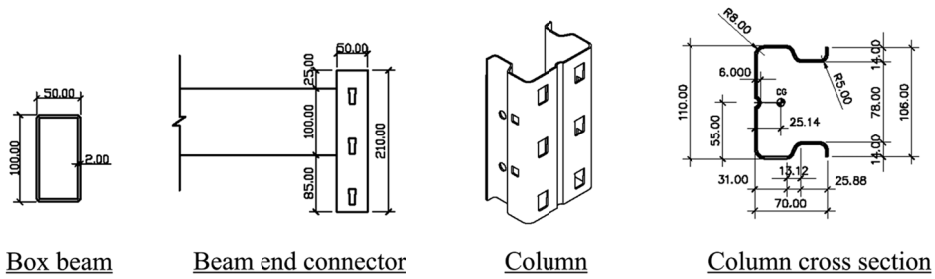
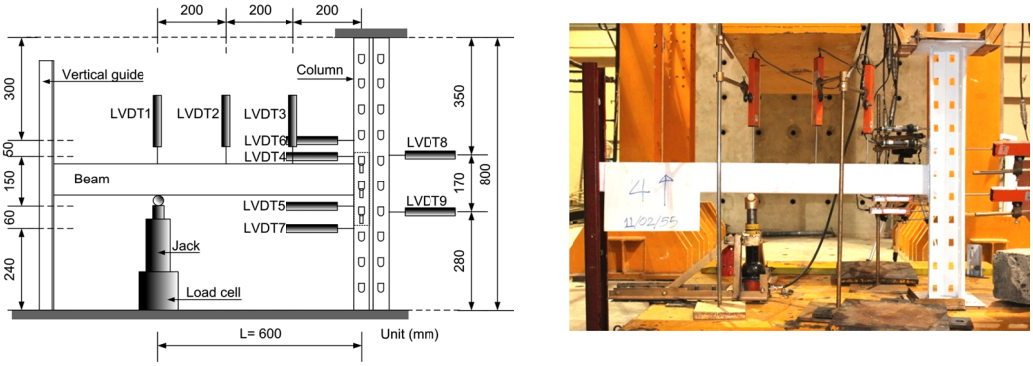


Figure 1: Component of the tested specimens (dimensions in (mm)).

2.1. Cantilever test

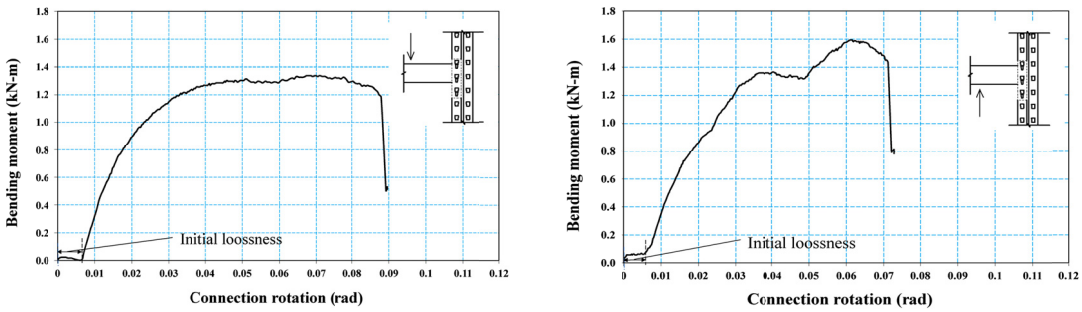
The cantilever test provides a simple method of determining the connection strength and stiffness. The cantilever test setup consists of a short cantilever of pallet beam connected to the center of a short length of a column. Both ends of the column are rigidly supported. The load is applied monotonically by a hydraulic jack placed on a load cell. The free end of the beam is constrained by a vertical guide to prevent an undesirable out-of-plane movement of the beam. The applied loads are recorded at each increment of loading until the failure is occurred at the connection. Displacement transducers are mounted to measure beam and column deflections. The rotation of the connection is calculated from the deflections for each load step. Figure 2 shows the general layout of the experimental setups and the arrangement of the transducers. Full details of the experimental results are available in an earlier paper by the authors (Asawasongkram 2012).



(a) Transducer arrangement. **(b) Actual test setup.**

Figure 2: Cantilever test setup.

The cantilever tests are conducted of six connection samples which consist of three for hogging moment testing and three for sagging moment testing. The samples of experimental results of moment-rotation curve are shown in Figure 3. The experimental results show that, the connection exhibited looseness at the initial stage because the steel tabs are not fit in the column slot. The looseness is overcome when the rotation reached an approximately 0.006 rad. The initial looseness of the connection is also found in the previous of experimental studies (Bernuzzi and Castiglioni 2001; Bajoria and Talikoti 2006; Prabha et al. 2010). The strength and stiffness of the connections are different under hogging and sagging moments due to the asymmetric of the connection geometry. The failure took place when the tab in the tension side was cut by the column perforation. The results also show that the average of plastic rotation capacity of the connection is about 0.08 rad. The connection stiffness and the ultimate moment capacity are tabulated in Table 1. In this study, the connection stiffness is determined by the concept suggested by FEM (FEM 1998) after the initial looseness is terminated. The FEM uses an iterative graphical procedure that approximately balances the areas below the actual and ideal curves up to the failure point.



(a) Hogging moment. **(b) Sagging moment.**

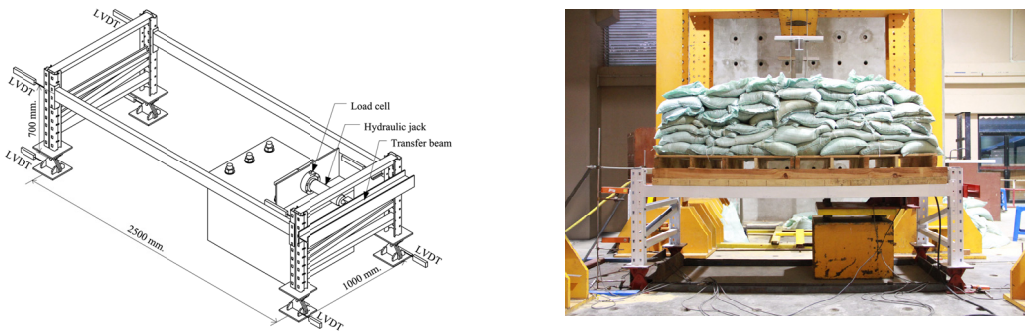
Figure 3: Example of moment-rotation curve from cantilever test.

Table 1: Beam-to-column connections test results from cantilever test

Test no.	Type of loading	Stiffness (kN-m/rad)	Average stiffness (kN-m/rad)	Ultimate moment capacity (kN-m)	Average ultimate moment capacity (kN-m)
1	Hogging moment	51.42		1.44	
2	Hogging moment	51.54	49.50	1.34	1.37
3	Hogging moment	45.52		1.32	
4	Sagging moment	45.33		1.36	
5	Sagging moment	48.54	44.87	1.59	1.53
6	Sagging moment	40.75		1.63	

2.2. Portal test

Under the portal test, the connection is subjected to shear force, bending moment and axial force thus representing the actual field conditions. A portal test setup is shown in Figure 4. Two portal frames were mounted on hinges supports which are clamped to the strong floor. Three bracing element are connected between two portal frames by channel sections to prevent any displacement in the transverse direction. The vertical distance between the center of the hinges and the center of the beam is equal to 700 mm. The horizontal distance between the column centerlines is 2500 mm. The distance between two portal frames is 1000 mm. A horizontal rigid transfer beam bolted to the two columns is used to distribute the lateral loads equally to the two frames. Lateral loads are applied by a hydraulic jack placed on a load cell attached to a very rigid steel support and connected to the strong floor. Vertical loads are simulated by sand bags resting on standard wood pallet.



(a) Transducer arrangement. **(b) Actual test setup.**

Figure 4: Portal test setup.

Four types of content weight are used for the test series to investigate the effects of vertical loading level on strength and stiffness of beam-to-column connection. The 1st case is no vertical loading. The 2nd is "medium" loading level which has a total weight of 1 ton (2 kN/m/portal frame). The 3rd is "high" loading level which has a total weight of 2 ton (4 kN/m/portal frame). The 4th is "very high" loading level which has a total weight of 2.5 ton (5 kN/m/portal frame). These vertical loading levels correspond to 0%, 40%, 80% and 100% of the allowable moment of the portal beam respectively. Four displacement transducers, LVDT1-LVDT4, are placed on column at the level of centerline of the portal beam to measure the lateral displacement of the portal frame. Additional displacement transducers, LVDT5-LVDT8, are placed at the base of the column to check the sliding of the column. The lateral loads and lateral displacements are recorded at each incremental of loading until the failure is occurred. The experimental moment-rotation curves are given in Figure 5. The main characteristics of the moment-rotation curves are shown in Table 2. The moment at the connection are expressed as (Krawinkler et al. 1979)

$$M = \frac{H}{2}h + P\delta \tag{1}$$

The average rotation of the beam-to-column connection is given by

$$\theta = \frac{\delta}{h} - \left(\frac{Mh}{3EI_c} + \frac{ML}{6EI_b} \right) \tag{2}$$

where H is the lateral load applied to one portal frame, h is the vertical distance from center of hinge support to the center of portal beam, P is the axial force in the column due to vertical loads, δ is the lateral displacement at the center of the portal beam. δ is taken as the average recorded displacement obtain from LVDT1-LVDT4 as shown in Figure 4(a).

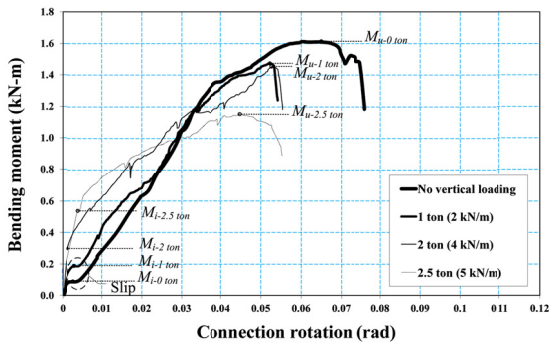


Figure 5: Moment-rotation curve for portal test with four vertical loading levels.

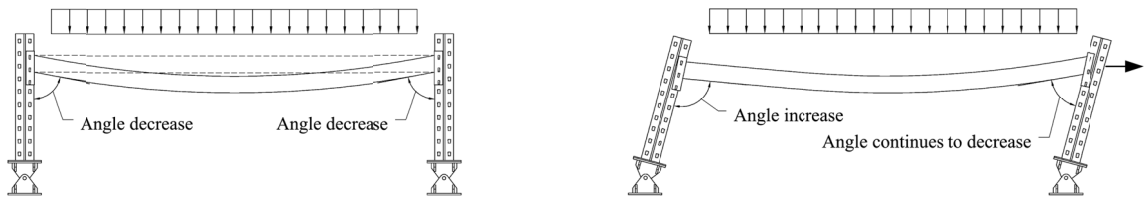
Table 2: Beam-to-column connections test results from portal test

Type of vertical loading	Moment at the initial stage, M_i (kN-m)	Ultimate moment capacity, M_u (kN-m)	M_i/M_u (%)
No vertical loading	0.081	1.612	5.0
1 ton (2 kN/m)	0.184	1.473	12.5
2 ton (4 kN/m)	0.286	1.439	19.9
2.5 ton (5 kN/m)	0.538	1.152	46.7

From the portal testing, the following observation can be made. The structure with higher vertical loading level has a lower connection capacity than the structure with lower vertical loading level. For example, the ultimate moment capacity of the very high loading is 70% comparing with the ultimate moment capacity of the no vertical loading. In the higher vertical loading levels, both sides of the beam-to-column connections have a higher initial hogging moment and a higher shear force acting on a positive direction. When the lateral load is subsequently applied, the left side connection would be sagging moment and a shear force acting on a negative direction whereas the right side connection would be a hogging moment and a shear force acting on a positive direction. For the right side connection, the hogging moment and shear force due to the lateral load will combine with a high initial hogging moment and a high initial shear force due to the vertical load. The combinations of bending moment and shear force produce the right side connection reaches their ultimate moment capacity prior to the other lower vertical loading levels.

The portal frame deflected shape under the vertical and lateral load are shown in Figure 6. At the initial, the angle between the beam and the column decrease both on the left and right connections due to the application of vertical loads. When the structure subjected to an increasing lateral load, an angle on the left side connection starts to increase and the angle on the right side connection continue to decrease. The failure occurred on the right side connection at the steel tab placed farther above the neutral axis.

Another observation is that the portal test exhibits a high initial stiffness at the initial stage due to the tightening of the vertical load. In this study, the effect of the vertical load on the initial stiffness is represented by the ratio of the moment at the initial stage to the ultimate moment capacity (M_i/M_u). The effect of the vertical load effect is low, which M_i/M_u equal to 5% and 12.5%, for the no vertical loading and the medium vertical loading. The vertical load has a certain effect, which M_i/M_u equal to 19.9%, for the high vertical loading. The effect of the vertical load is rather high, which M_i/M_u equal to 46.7%, for the very high vertical loading. At the end of the initial stage, the tightening of the connection is released by the moment due to the lateral load, then the stiffness decrease. The moment-rotation curve show the "slip" at the end of the initial stage for the no vertical loading and the medium vertical loading. The slip represent by a short flat line in the moment-rotation curve. This slip come from the steel tabs are not perfectly fit with the column slot. However there is no slip for the high and very high vertical loading due to a large friction between the steel taps and column slot from a high value of vertical loadings.



(a) Application of vertical load. **(b) Application of lateral load.**

Figure 6: Portal frame deflected shapes.

3. STRUCTURAL ANALYSIS

The correlation of the experimental test results obtained from cantilever tests and portal tests is one of the main objectives of this study. The cantilever tests distinguish between the hogging and sagging moment-rotation of the connections whereas the portal tests give a mean value of the moment-rotation of the connections. To compare the experimental results indirectly, a non-linear pushover analysis of a single story frame is performed by means of a computer program SAP2000 (CSI 2009). The results between the portal test and the numerical analysis using beam-to-column connection obtained from the cantilever test are investigated. Non-linear behavior of the beam-to-column connection is modeled by a non-linear rotational link element. The link element connected to the end of beam and the end of column as shown in Figure 7. The characteristics of link elements are obtained from the cantilever test. The effects of geometric nonlinearities and material nonlinearities are also taken into account in the numerical model. A nonlinear moment-rotation relation of a connection is modeled by a tri-linear model to account for the effects of the initial looseness. The tri-linear model is illustrated in Figure 8. The value of k_1 is the average stiffness in the initial looseness stage. The value of k_2 is the average connection stiffness obtained by the concept suggested in FEM (FEM 1998). The parameters of the tri-linear model (k_1, k_2, θ_i, θ_y, M_i, M_u) obtained from experimental results of the cantilever test. The pushover analysis results compare with the experimental results from the portal test as illustrated in Figure 9.

The analytical results using beam-to-column connections from the cantilever test show a good correlation with the experimental results from the portal test for no vertical loadings and medium vertical loadings. For high and very high vertical loadings, the analytical results do not produce a good correlation with the experimental results from the portal tests. The experimental results from portal tests produce a higher stiffness approximately two times higher than the analytical results for the high and very high vertical loadings. The portal tests also produce a lower strength than the analytical results for very high vertical loadings. These results show a limit of a cantilever test method for high and very high vertical loadings. As explained in section 2.2, the cantilever tests can not represent the effect of a tightening at the connection and a combination of shear and bending moment due to the vertical service loading. These effects lead to a non-correlation of the analytical results compared to the test results from portal tests for high and very high vertical loading level.

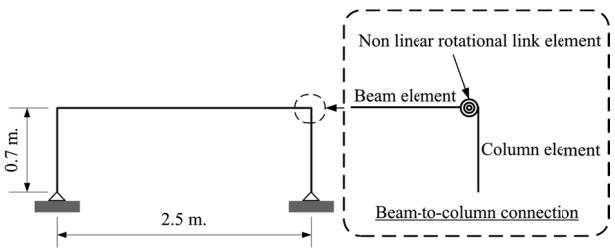


Figure 7: Configuration of the case study frame and beam-to-column joint modeling.

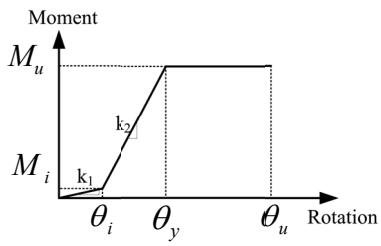
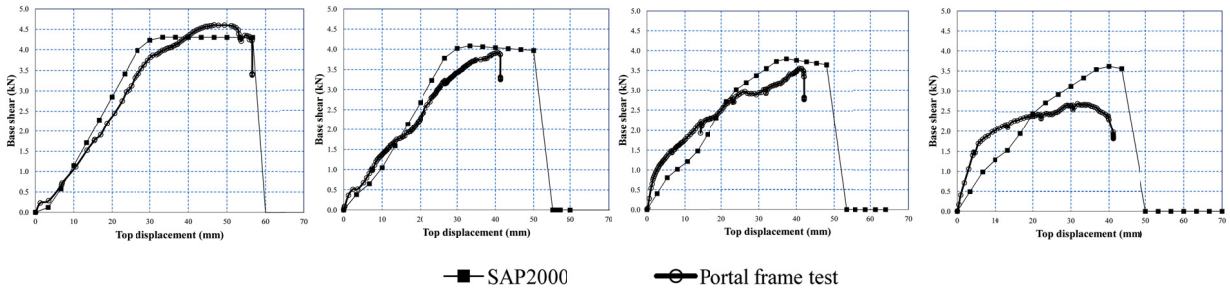


Figure 8: Tri-linear model for moment-rotation of beam-to-column connections.



(a) No vertical loading **(b) 1 ton (2 kN/m)** **(c) 2 ton (4 kN/m)** **(d) 2.5 ton (5 kN/m)**

Figure 9: Relation between experimental results from portal tests and numerical analysis results using beam-to-column connection from cantilever tests.

4. CONCLUSIONS

This paper presents experimental results of a typical steel storage rack beam-to-column connection using the cantilever test and the portal test method. The results from a pushover analysis of a single story frame using a moment-rotation relation of beam-to-column connections obtained from cantilever tests are compared with the experimental results from portal tests. The analytical results show a good correlation with the experimental results for low to medium vertical loading levels whereas it shows a poor correlation for high to very high vertical loading levels. It is suggest that for a lateral analysis such as a seismic analysis of this type of the structure especially under a high or very high vertical service loading, the portal tests is recommended to get the reliable and conservative of the moment-rotation of the connection for the analysis.

REFERENCES

AS4084 (1993). Steel storage racking. Standards Australia. Sydney (Australia).

Asawasongkram A and Premthamkorn P (2012). Behavior of steel storage rack connections under monotonic loading. Proceeding of the 17th National Convention on Civil Engineering, Udonthani, Thailand, Paper No.STR042.

Bajoria KM and Talikoti RS (2006). Dermination of flexibility of beam-to-column connectors used in thin walled cold-formed steel pallet racking systems. Thin- Walled Structures. 44(3), pp. 372-380.

Bernuzzi C and Castiglioni CA (2001). Experimental analysis on the cyclic behaviour of beam-to-column joints in steel storage pallet racks. Thin-Walled Structures. 39(10), pp. 841-859.

CSI Computer & Structures Inc. (2009). SAP2000 Linear and nonlinear static and dynamic analysis of three-dimensional structures. Berkeley (CA), Computer & Structures, Inc.

FEM Section X (1998). Recommendations for the design of steel static pallet racking and shelving. Brussels (Belgium).

Harris E (2006). Sway behavior of high rise steel storage racks. Ph. D. thesis, University of Sydney.

Krawinkler H, Cofie NG, Astiz MA and Kircher CA (1979). Experimental study on the seismic behavior of industrial storage racks. Report no. 41, The John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Standford University, Standford.

Markazi FD, Beale RG and Godley MHR (1997). Experimental analysis of semi-rigid boltless connectors. Thin-Wall Structures. 28(1), pp. 57-87.

Prabha P, Marimuthu V, Saravanan M and Jayachandran SA (2010). Evaluation of connection flexibility in cold formed steel racks. Journal of Constructional Steel Research. 66(7), pp. 863-872.

RMI (2008). Specification for the design, testing and utilization of industrial steel storage racks. Charlotte (USA). Rack Manufacturers Institute.