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Experimental Analysis of Beam-to-upright Connections in Cold-formed Steel Storage Pallet Racks

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Abstract

A research program is currently in progress at Department of Building Engineering of Tongji University with the aim of investigating the behavior of cold-formed steel storage pallet racks under static and dynamic loading. This paper presents preliminary experimental analysis on the monotonic behavior of beam-to-upright connections. In the experimentation, the set-up was specially designed to accommodate precise requirement of boundary conditions and the measurement method was refined from the general ones used in rack design codes. It is shown that deformation modes of the connections were similar before failure while the failure modes were different depending on the specific constructional details. Moment-rotation characteristic curves are obtained and compared. On the base of these curves, the main parameters controlling the stiffness and moment capacity of connections, such as thickness of upright section, depth of pallet beam section, construction of beam end connector (mainly the number of tabs) and the loading direction are discussed.

Introduction

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Cold-formed steel storage pallet rack structure is widely used in industry for storing and retrieving goods. It mainly consists of uprights which are often perforated along axis and beams often in the shape of rectangular boxes (Yu and LaBoube 2010). The beams are connected to uprights by beam end connectors which are welded onto the ends of beams and often insert into upright perforations by boltless tabs. Furthermore, a safety device is used to avoid pulling out of beam from upright in the presence of accidental uplift force. A typical beam-to-upright connection is shown in Figure 1.

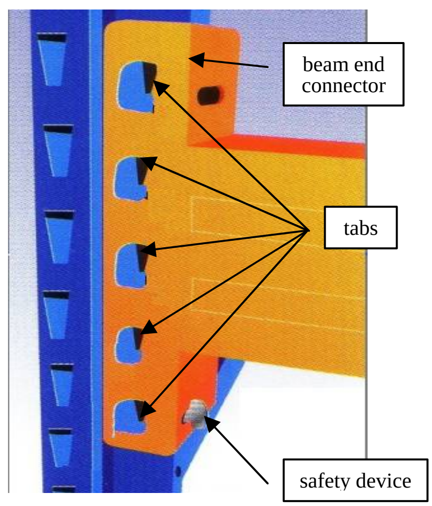


Figure 1 Beam-to-upright connection

The storage racks are often unbraced in the down-aisle direction for spacial need so that the stability of storage racks in the down-aisle direction is largely provided by the beam-to-upright connections and by the base plate connections (Baldassino and Bernuzzi 2000). An understanding of the moment-rotation characteristics of the beam-to-upright connection is important. There is currently no analytical method effectively available to determine these characteristics, such as stiffness and moment capacity of the connection, partly due to the diversity of beam-to-upright connections. The main international storage rack design specifications suggest carrying out experiment to obtain properties of these connections (AS 4084 1993; RMI 2008; EN 15512 2009). Two alternative beam-to-upright connection experiment methods, i.e. portal frame test and cantilever test, are available, and which one to use is decided by designers and researchers.

The portal frame test is included in AS 4084 1993 and RMI 2008, but not in EN 15512 2009. As this method can only determine the mean stiffness of a number of connections and does not distinguish between the behavior of the two connections on either side of the portal, which may have different characteristics, it is unsuitable for the detailed analysis of connection behavior(Abdel-Jaber et al. 2006). The principal is explained by Gilbert and Rasmussen (2009).

The cantilever test is accepted by all specifications even though some minor differences in the test set-up dimensions and procedures exist. Many researchers have used this method to investigate the behavior of beam-to-upright connections under monotonic or cyclic loadings (Abdel-Jaber et al. 2006; Bernuzzi and Castiglioni 2001; Krawinkler et al. 1979; Markazi et al. 1997; Prabha et al. 2010).

As the usage of cold-formed steel storage pallet racks are becoming popular but few research works have been done in China, a research program is currently in progress at Department of Building Engineering of Tongji University. As the base of the research program, experimental evaluation of beam-to-upright connection under static loading is presented in this paper. The experiment is based on cantilever test method, considering some special boundary conditions and measuring methods.

Laboratory experimentation

Specimen details

A total of 21 specimens were tested first, each consisting of a beam with a length of 800mm with a beam end connector connected onto one end by welding, an upright with a length of 760mm, and a safety device. The parameters considered in the experiment were thickness of upright section, depth of beam section, number of tabs on beam end connector (i.e. height of beam end connector) and loading direction (i.e. hogging or sagging). All specimens were grouped and identified and the specimen ID is listed in Table 1. Take 1.8C5-B120-4T3.0-H as an example, 1.8C5 indicates the upright section is C5 type with the thickness of 1.8mm; B120 represents the depth of beam is 120mm; 4T3.0 means beam end connector has 4 tabs, i.e. the height of beam end connector is 200mm (4 times 50mm) and 3.0 means the thickness of beam end connector is 3mm which is identical for all specimens; and H means the loading direction is hogging.

Table 1 Specimen ID

Group	Specimen ID	No. of identical specimens
S1	1.8C5-B120-4T3.0-H	3
	1.8C5-B120-4T3.0-S	1
S2	2.5C5-B120-4T3.0-H	3
	2.5C5-B120-4T3.0-S	1
S3	1.8C5-B105-4T3.0-H	3
	1.8C5-B105-4T3.0-S	1
S4	1.8C5-B145-4T3.0-H	3
S5	1.8C5-B120-3T3.0-H	3
S6	1.8C5-B120-5T3.0-H	3

The uprights and beams of specimens were fabricated from cold-formed steel. The types of upright and beam sections are given in Figure 2 and Figure 3 respectively. The beam end connectors were made of hot-rolled steel. Details of the beam end connectors and their positions with respect to the beams are shown in Figure 4. Other detailed dimensions are omitted for commercial reasons.

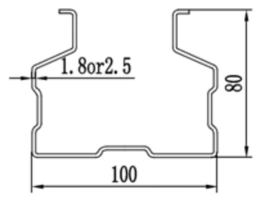


Figure 2 Upright section of C5 type

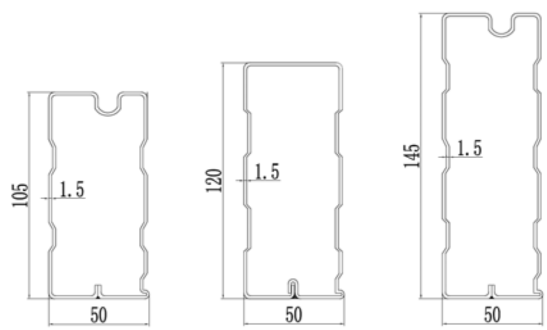


Figure 3 Three types of beam sections: B105, B120 and B145

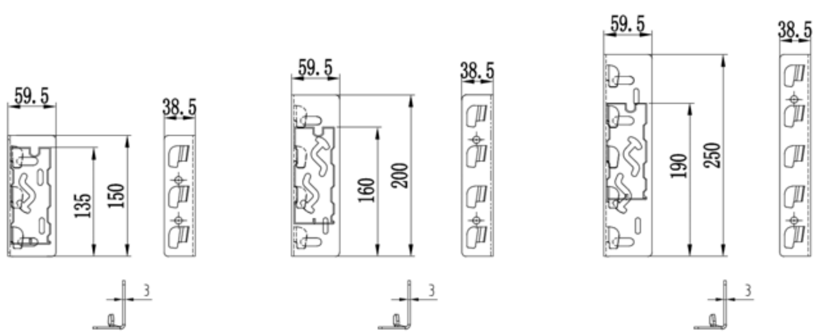


Figure 4 Three types of beam end connectors: 3T, 4T and 5T

Test set-up

The schematic diagram of the test set-up is given in Figure 5. The upper end of the actuator is connected onto a mechanism, frictional effect of which is very small, making the actuator free to move horizontally to keep the applied load vertical when the beam is deforming in the test. The lateral bracing is used to restrain the lateral movement of the beam. The effect of frictional force between beam and lateral bracing on the moment of beam-to-upright connection is required to be very small so that the lateral bracing is specially designed. As shown in Figure 6, the beam is clipped by two pieces of stainless steel plate, and four sleek balls are used to brace the stainless steel plate on each side. With this device it is reasonable to deem that the frictional force between beam and lateral bracing is small enough. Figure 7 shows the general arrangement of the specimen and test set-up.

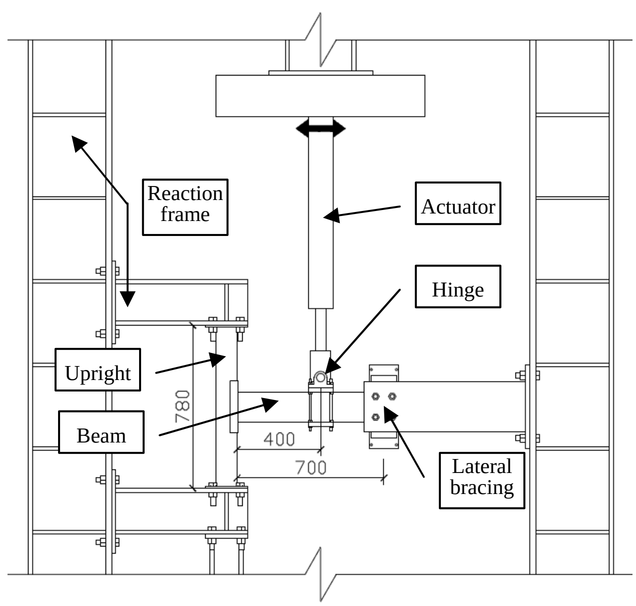


Figure 5 Schematic diagram of the test set-up

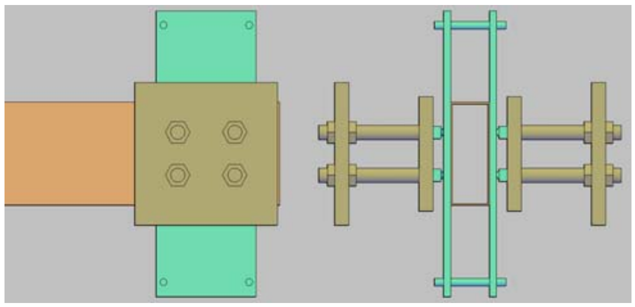


Figure 6 Schematic diagram of the lateral bracing

Figure 7 Cantilever test specimen and set-up

Measurement

The applied load was measured by a 2T load transducer at the end of the actuator. Strain gauges were attached to the top and bottom surfaces of three sections of the beam to monitor the connection moments.

The rotation of beam-to-upright connection is defined as the relative rotation between beam axis and upright axis at their intersection. Usually the rotation is measured through displacement transducers attached to beam (Markazi et al. 1997) or beam end connector (EN 15512 2009; Markazi et al. 2001). The flexibility of the beam or beam end connector needs to be taken into account in order to obtain the true rotation. Abdel-Jaber et al. (2006) compared and analyzed the two alternative methods of measuring the rotation of the connection and derived appropriate correction formulae.

The authors present a refined measurement method as shown in Figure 8. The connection rotation can be obtained by

$$\Phi = \Phi_b - \Phi_c \quad (1)$$

$$\Phi_b = 0.5((D1-D3)/h_1 + (D2-D4)/h_2) \quad (2)$$

$$\Phi_c = (D5-D6)/h_3 \quad (3)$$

$$\Phi_b' = (D7-D8)/h_4 \quad (4)$$

where Φ is the rotation of connection, Φ_b is the rotation of beam axis at the connection, Φ_c is the rotation of upright axis at the connection, Φ_b’ is the rotation of beam axis away from the connection which includes the component of beam flexural deflection, Di is the value of the ith displacement transducer, h_i is the distance between corresponding displacement transducers.

It is found in following test that Φ_b is almost the same as Φ_b’ once Φ_b’ is modified by excluding the flexural deflection. So formulae (1), (2) and (3) are proper and simple to use to obtain the rotation of the beam-to-upright connection.

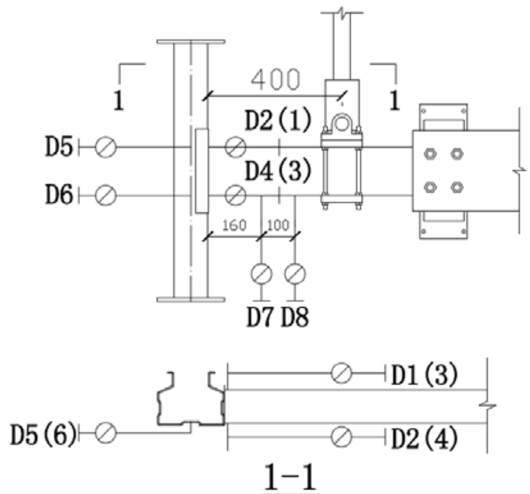


Figure 8 Arrangement of displacement transducers

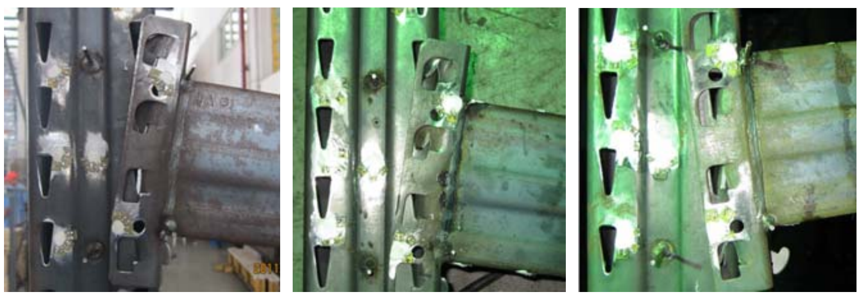
Experimental results

The load was applied by an electric actuator fitted on a load transducer 400mm from the face of the upright. In each test, the load was applied incrementally with a speed of 0.5mm/min at the beginning and 1~2mm/min after the maximum load. The load, strain and displacement were recorded electronically every one second through a data logger. The test was terminated when the load dropped to 75% of the maximum load or the deformation of the specimen was so serious that it was unfit for loading any more.

Failure modes

All of the specimens exhibited similar deformation modes before failure. The tabs distorted making the most contribution for the rotation of connection. Beam end connector and the flange of upright presented flexural deformation.

But the failure modes of specimens were not consistent for different parameters considered in the experiment. For the hogging loading specimens, the crucial parameter for failure mode was the thickness of upright. The failure mode was the crack of upright perforation for smaller thickness of upright (1.8mm) and crack of the top tab for bigger thickness of upright (2.5mm) independent of the depth of beam section and the number of tabs. For the sagging loading specimens, the failure mode was the crack of the bottom tab and then pulling out of the safety device. Test photo pictures for failure modes are given in Figure 9.

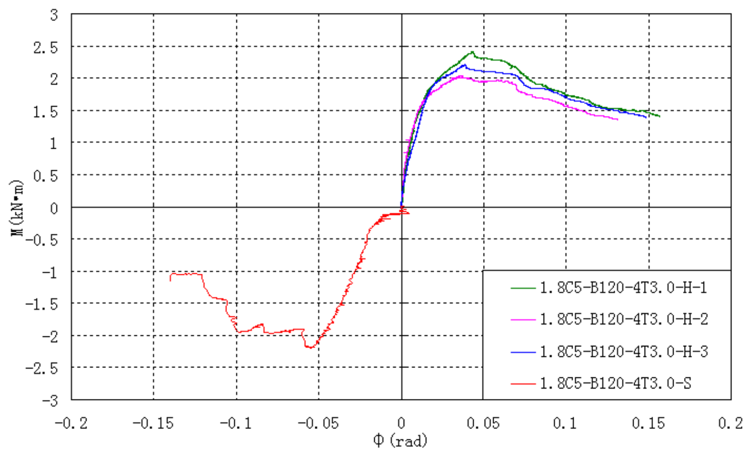


(a) **(b)** **(c)**

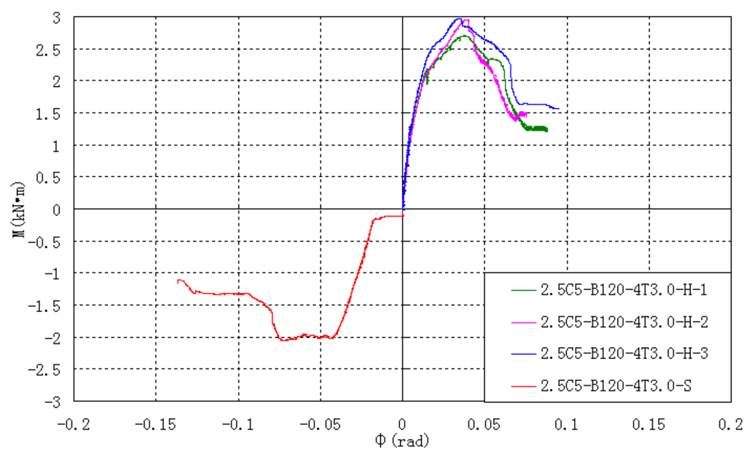
Figure 9 Test photo pictures for failure modes: crack of (a) upright perforation (b) top beam end connector tabs and (c) bottom beam end connector tabs

Moment-rotation curves

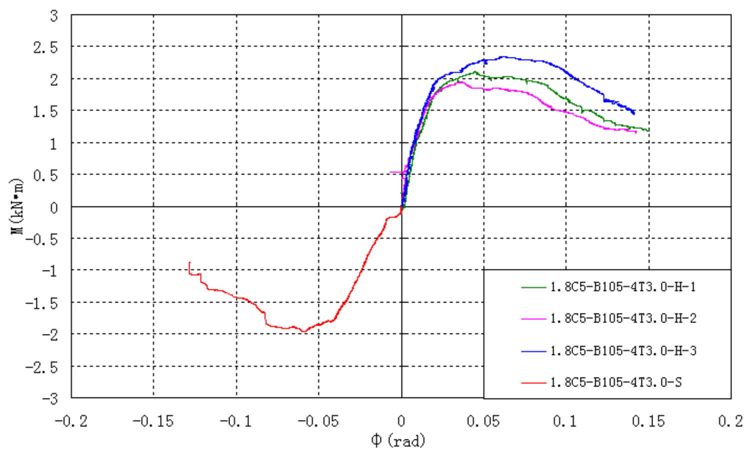
The recorded data was used to plot the moment-rotation curves. The results of the tests are shown in Figure 10. These curves were used to determine the stiffness and moments capacity of the beam-to-upright connections. For hogging specimens the stiffness was taken as the gradient of a line passing through the original point and a point on the moment-rotation curve at half the failure moment, while for sagging specimens the method was the same except that the original point was moved to the point on the curve where the initial looseness was just over. Table 2 shows a summary of the results.


3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
M(kN•m)
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Φ(rad)
1.8C5-B120-4T3.0-H-1
1.8C5-B120-4T3.0-H-2
1.8C5-B120-4T3.0-H-3
1.8C5-B120-4T3.0-S

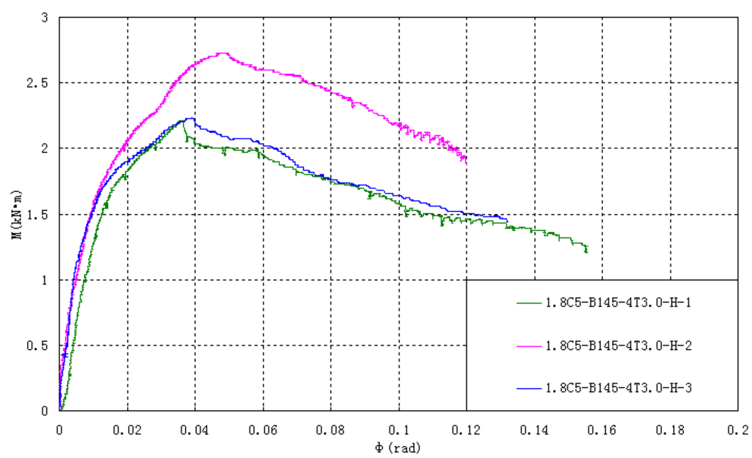
(a) S1


3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
M(kN•m)
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Φ(rad)
2.5C5-B120-4T3.0-H-1
2.5C5-B120-4T3.0-H-2
2.5C5-B120-4T3.0-H-3
2.5C5-B120-4T3.0-S

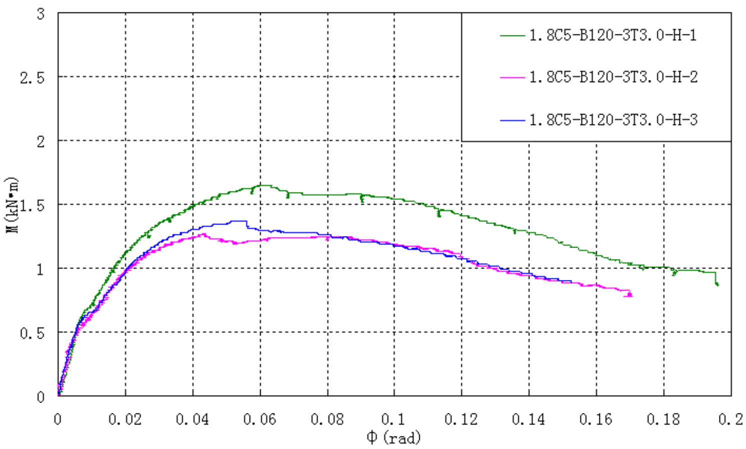
(b) S2


M (kN•m)
Φ (rad)
1.8C5-B105-4T3.0-H-1
1.8C5-B105-4T3.0-H-2
1.8C5-B105-4T3.0-H-3
1.8C5-B105-4T3.0-S

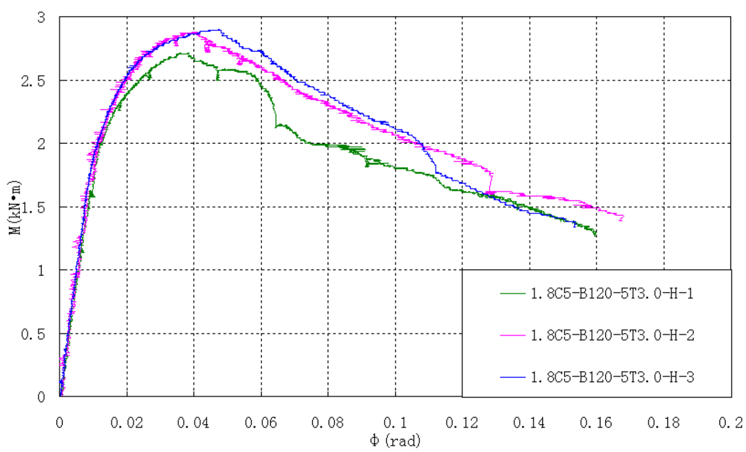
(c) S3


M (kN•m)
Φ (rad)
1.8C5-B145-4T3.0-H-1
1.8C5-B145-4T3.0-H-2
1.8C5-B145-4T3.0-H-3

(d) S4



(e) S5



(f) S6

Figure 10 Moment-rotation curves for specimens

Table 2 Beam-to-upright connections test results

Group	Specimen ID	No.	Stiffness(kN•m/rad)	Average	Moment capacity(kN•m)	Average
S1	1.8C5-B120-4T3.0-H	1	154.010	162.606	2.405	2.214
		2	210.840		2.029	
		3	122.969		2.208	
	1.8C5-B120-4T3.0-S	1	56.812	56.812	2.198	2.198
S2	2.5C5-B120-4T3.0-H	1	200.595	205.332	2.702	2.875
		2	193.952		2.953	
		3	221.449		2.971	
	2.5C5-B120-4T3.0-S	1	81.012	81.012	2.052	2.052
S3	1.8C5-B105-4T3.0-H	1	108.466	121.643	2.107	2.131
		2	126.738		1.946	
		3	129.726		2.341	
	1.8C5-B105-4T3.0-S	1	50.437	50.437	1.969	1.969
S4	1.8C5-B145-4T3.0-H	1	129.022	174.222	2.211	2.391
		2	172.641		2.730	
		3	221.003		2.232	
S5	1.8C5-B120-3T3.0-H	1	66.565	63.765	1.646	1.427
		2	64.666		1.267	
		3	60.063		1.368	
S6	1.8C5-B120-5T3.0-H	1	177.503	186.814	2.713	2.829
		2	185.032		2.875	
		3	197.907		2.899	

Discussion on parameters

Despite variation of test result of specimens in a group, the comparison of stiffness and moment capacity can be made from an average sense.

For the X-B120-4T3.0-H specimens(X represents the variable parameter), the increase in upright thickness from 1.8 to 2.5mm has resulted in 26% and 30%

increase in the stiffness and moment capacity, respectively.

For the 1.8C5-X-4T3.0-H specimens, the increase in beam depth from 105 to 120mm has resulted in 33% and 4% increase in the stiffness and moment capacity, respectively. Further increase to 145 mm has increased the stiffness and moment capacity by 43% and 12%, respectively.

For the 1.8C5-B120-X-H specimens, the increase in the number of tabs from 3 to 4 has resulted in 155% and 55% increase in the stiffness and moment capacity, respectively. Further increase to 5 has increased the stiffness and moment capacity by 193% and 98%, respectively.

For the sagging specimens, the stiffness and moment capacity is lower than that of hogging specimens. The ratio of sagging stiffness to that of hogging is 0.35, 0.39 and 0.41 for S1, S2 and S3 group respectively. The ratio of sagging moment capacity to that of hogging is 0.99, 0.71 and 0.92 for S1, S2 and S3 group respectively. Furthermore, all sagging specimens presented initial looseness which is not the case for all hogging specimens. The reason for this may be that the construction of tabs and upright perforations is well designed.

Conclusions

From the experimental analysis of 21 beam-to-upright connections, the following conclusions are made.

The moment-rotation characteristic of a beam-to-upright connection is determined by all of its components, including upright, beam and especially beam end connector.

The thickness of upright is crucial for failure mode of hogging connection, deciding which part will crack first.

Increasing the thickness of upright, the depth of beam or the number of tabs leads to considerable increase in the stiffness of connection, most contribution coming from the number of tabs. So tabs must be arranged so as to resist the applied loading.

The influence of the depth of beam on the moment capacity of connection is limited comparing with that of the thickness of upright and the number of tabs.

The initial looseness can be avoided through special design of construction details of connection components.

References

Abdel-Jaber, M., Beale, R. G., and Godley, M. H. R. (2006). "A theoretical and experimental investigation of pallet rack structures under sway." *Journal of Constructional Steel Research*, 62(1-2), 68-80.

AS 4084. (1993). *Steel storage racking*, Standards Australia, Sydney, Australia.

Baldassino, N., and Bernuzzi, C. (2000). " Analysis and behavior of steel storage pallet racks. " *Thin-Walled Structures*, 37(4), 277-304.

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

EN 15512. (2009). *Steel static storage systems-Adjustable pallet racking systems-Principles for structural design*, European Committee for Standardization (CEN), Brussels, Belgium.

Gilbert, B. P., and Rasmussen, K. J. R. (2009). "Experimental test on steel storage rack components." School of Civil Engineering, The University of Sydney, Research Report R899, Australia.

Krawinkler, H., Cofie, N. G., Astiz, M. A., and Kircher, C. A. (1979). "Experimental study on the seismic behavior of industrial storage racks." The John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering, Stanford University, Report No.41, California.

Markazi, F. D., Beale, R. G., and Godley, M. H. R. (1997). "Experimental analysis of semi-rigid boltless connectors." *Thin-Walled Structures*, 28(1), 57-87.

Markazi, F. D., Beale, R. G., and Godley, M. H. R. (2001). " Numerical modelling of semi-rigid boltless connector." *Computers & Structures*, 79(26-28), 2391-2402.

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

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

Yu, W. W., LaBoube, R. A. (2010). *Cold-Formed Steel Design, 4th Edition*, John Wiley & Sons, New York, NY.