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Experimental investigation into steel storage rack beam-to-upright bolted connections

Liusi Dai[1], Xianzhong Zhao[2] and Chong Ren[3]

Abstract

For unbraced steel storage racks, the down-aisle stability depends largely on the performance of beam-to-upright connections and column bases. Boltless connections are generally used in order to make rack structures easy to assemble and feasible to adjust the storey height. Recently, storage racks are designed to carry large amounts of goods and they are therefore raise a considerable height, which makes the improvement of the structural stability to be sufficiently important. Under the circumstances, tab-connected beam-to-upright connections with bolts are gradually used in steel storage racks. Compared with boltless connections, the stiffness, strength and ductility of the bolted connections are improved to some extent. This paper presents an experimental investigation into the moment-rotation characteristic of steel storage rack beam-to-upright bolted connections under monotonic loads. Seven groups of specimens were tested with different constructional details and three identical specimens were repeated for each group. Moreover, the single cantilever test method was employed to study the rotational behaviour of connections. Effects of various parameters, such as upright thickness, beam height and tab numbers on connection behaviour are discussed and presented in this paper. The experiments show that the failure modes of bolted beam-to-upright connections depend on the relative thickness between the upright and beam-end-connector, as well as the relative height between the beam and beam-end-connector. Furthermore, the results obtained from the present study highlight that the behaviour of connections, such as

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stiffness and ultimate moment capacity, are considerably influenced by the specific constructional details.

Introduction

One of the significant application of cold-formed steel is steel storage racks (Hancock, 2003), which has been widely used in fields of warehousing. In practice, various rack structures, such as pallet, drive-in/drive-through, cantilever and high-rise racks are used. Uprights, beams, beam-to-upright connections and column bases are the main components of rack structures. In pallet racks (see Figure 1), beams are welded to beam end connectors and uprights are perforated along the length which allows the beam to be connected at variable heights. In order to allow each pallet always accessible to racks, steel storage racks are usually unbraced in down-aisle directions. Therefore, the down-aisle stability of rack structures depends largely on the performance of beam-to-upright connections and column bases (Bernuzzi et al. 2000).

The mechanical semi-rigid beam-to-upright connections are generally employed in steel storage racks for their convenience in assembly and adjustment. Boltless beam-to-upright connections were categorised into four classes based on the connector features by Markazi et al. (1997). Due to the complex nature and variable geometrical details, connection design largely relies on experimental tests. Two test methods, i.e. cantilever tests and portal tests, are recommended in AS 4048 (2012) and RMI (2012). Considering the portal test determines the average stiffness of the connections (Abdel-Jaber et al. 2006), only cantilever test method is proposed in EN 15512 (2009). Substantial experimental investigation into the behaviour of boltless beam-to-upright connections were conducted by Markazi et al. (1997), Bernuzzi and Castiglioni (2001), Aguirre (2005), Bajoria and Talikoti (2006) and Zhao et al. (2014). The researchers have studied the stiffness, the moment capacity and the hysteretic characterisation of connections in steel storage racks.

However, with the advance of modern logistic industry, storage racks are expected to carry increasingly more goods. For this reason, they are required to increase the height, which results in the necessity of the improvement in the structural stability. Under these circumstances, tab-connected beam-to-upright connections with bolts are gradually used in steel storage racks to improve the connection behaviour. Few studies on bolted connections used in rack structures were presented. Gilbert and Rasmussen (2010) performed portal tests on bolted connections applied in drive-in storage racks. The results showed that compared with tab connections, bolted connections have higher moment capacity and stiffness. Figure 1 illustrates the typical bolted connections widely used in China. Instead of boltless tab connections, a single bolt is applied to replace the safety device and designed to resist the accidental uplift loads. Whereas the bolt and tabs simultaneously participate in resisting the moment applied to the connection, which makes it complicated for engineers to predict the stiffness and strength of this type of connection. Due to limited research, the stiffness and strength of bolted connections are calculated by the same empirical equations used for boltless connections, which have been obviously underestimated. Therefore, studies on the behaviour of this type of connections employed in rack structures are highly concerned in order to establish a simplified design method of connections.

Figure 1. Pallet racks and typical beam-to-upright bolted connections

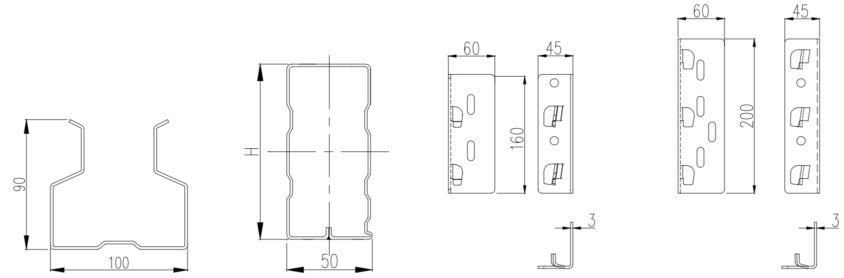
In this paper, an experimental investigation into the behaviour of steel storage rack beam-to-upright bolted connections is provided. The cantilever test method was adopted with special boundary conditions and refined measuring methods. A total of twenty-one individual tests, consisting of seven groups of three identical tests each, were conducted. This paper reports the static behaviour of beam-to-upright connections obtained from the tests, which includes the failure mode, the stiffness and the moment capacity. On the basis of the results, the influence of parameters, i.e. the thickness of the upright, the beam height and the tab number, on flexural behaviour of connections are studied.

Experimental Programme

As listed in Table 1, totally twenty-one individual specimens were tested, which are divided into seven groups. Each group includes three nominally identical specimens. Figure 2 shows the geometric details of uprights, beams and beam-end-connectors, respectively. Beams with the height of 105mm, 120mm and 145mm were considered, while two types of beam-end-connectors with various tab numbers were employed. The specimens were labelled to specify the connection details. Taking “2.3C2-B105-3T” as an example, “2.3C2” indicates column type C2 with the thickness of 2.3mm, “B105” represents the beam height of 105mm and “3T” refers to the tab number of three. In addition, the character “NB” corresponds to the specimen without bolts.

Table 1 Specimens

Specimen	Loading Protocol	Number of specimens	Variation
2.3C2-B105-3T	Monotonic	3	Beam height
2.3C2-B120-3T	Monotonic	3	
2.3C2-B145-3T	Monotonic	3	
1.8C2-B120-3T	Monotonic	3	Column thickness
2.8C2-B120-3T	Monotonic	3	
2.3C2-B120-2T	Monotonic	3	Tab number
2.3C2-B120-3T-NB	Monotonic	3	With or without bolts



C2: 100*90 B105/120/145 2T 3T

t=1.8mm, 2.3mm, 2.8mm t=1.5mm t=3.0mm t=3.0mm

(a) Upright (b) Beams (c) Beam-end-connectors

Figure 2 Dimensions of specimens

Figure 3 shows test setups employed in cantilever tests and the arrangement of displacement transducers. A 760mm long upright was fixed on cantilever support beams at each end and the beam was connected to the upright at its mid-span. The positive load was applied 400mm from the face of the upright by a 20kN displacement-controlled electric actuator. The actuator was fixed on the frictionless slider mechanism which made it move freely in horizontal directions. The locations of ten LVDTs were presented in Figure 3, as well as the equations for calculating the applied moment (M) and the rotation of connection (ϕ). LVDT9 monitors the horizontal displacement of the actuator, which is applied to modify the applied moment. LVDT1~LVDT4 measured the horizontal displacement of the beam end to determine the rotation of the beam axis at beam end (ϕ_{b1}). The rotation of column axis (ϕ_c) was derived from the readings of LVDT5 and LVDT6. LVDT7 and LVDT8 were mounted along the beam to calculate the rotation of beam axis (ϕ_{b2}). It should be noted that in many cases, with the load increasing the beam buckled at the end near the upright which resulted in the tilting of the stick used to fix the LVDT1~LVDT4. Afterwards the readings of LVDT1~LVDT4 were inaccurate and the rotation of connection was properly derived from the LVDT7 and LVDT8. In order to obtain the full-range force-displacement curves, displacement-controlled loading method was adopted based on the vertical displacement at the loading point. The specimen was tested at a slow loading rate of 0.5mm/min at the beginning and increased to 1~2mm/min after the peak load. The specimen was loaded incrementally until the load decreased by 50% or the loading cannot continue for the significant deformation of the specimen.

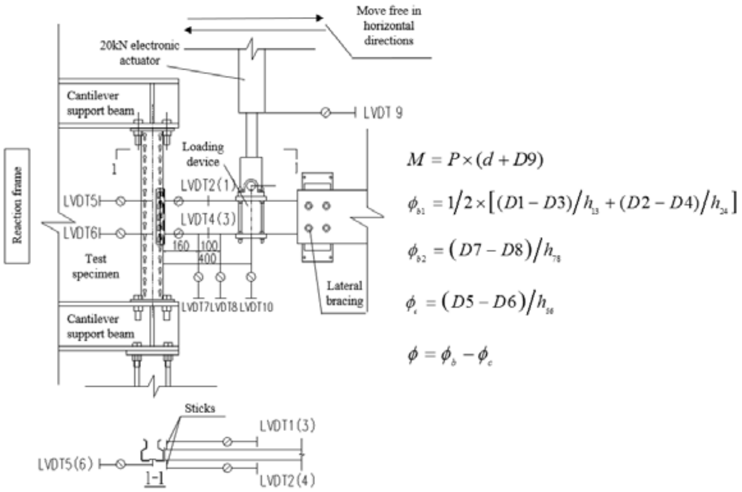


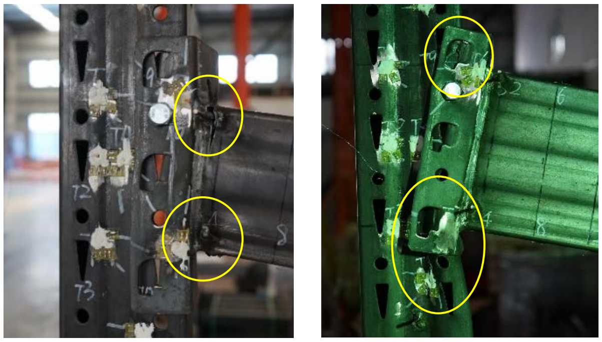
Figure 3 Test setups and displacement transducers locations
(D*i* represent the readings of LVDT*i*, *d* = the loading arm, *hij* = the distance between LVDT_i and LVDT_j)

Test results

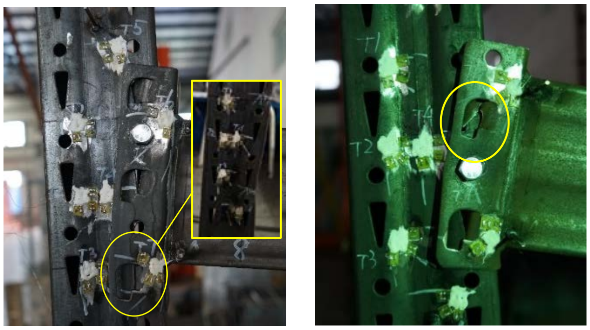
Experimental tests were carried out on twenty-one specimens, including different connection types, column thickness, beam heights and tab numbers. Figure 5 shows the moment-rotation curves of each specimen. Ductile failure mode was observed in most specimens, except the specimens “2.3C2-B120-2T3.0” and “2.3C2-B120-3T3.0-NB” experiencing broadly brittle failure. Taking specimen “2.3C2-B120-3T3.0” as an example to specify the typical moment-rotation characterisation of the bolted connection (see Figure 5). At first, the connection behave elastically. And then with the increased displacement, the moment-rotation curve entered into the non-linear phase, indicating that the stiffness decreased progressively due to the nonlinear deformations in various components, i.e. tab bending, buckling in certain areas of connector and upright, and the bolt slippage. The maximum load was reported for the beam buckling at the end near the upright. Afterwards owing to the load redistribution in the connection area, a significant plateau was observed. Finally, the weld cracked resulting in a dramatic decrease in the applied load.

Three types of failure modes and their combinations were observed in monotonic tests of bolted beam-to-upright connections (see Figure 4):

- (T) tab crack;
- (BE) beam end failure (beam buckling and weld crack);
- (C) upright buckling;
- Combination of failure modes above.



(a) T+BE (b) T+C

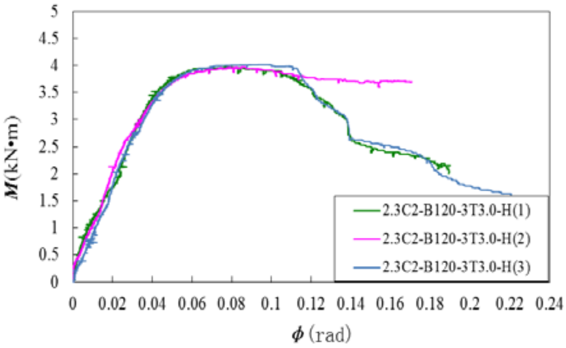


(c) C (d) T

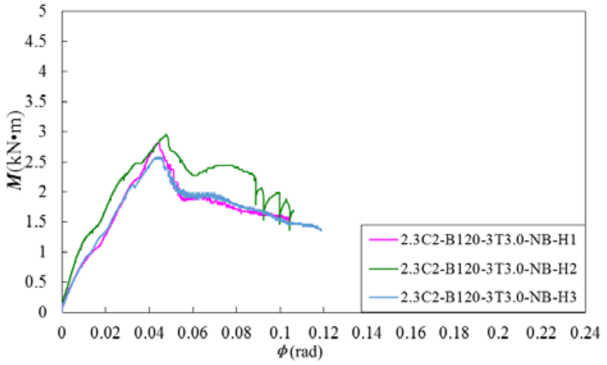
Figure 4 Failure modes

In monotonic tests, the common failure mode is the combination of tab crack (T) and beam end failure (BE). Tab crack was observed in most specimens. However, as for the specimen “1.8C2-B120-3T”, only buckling of the upright was observed because the strength of the upright was lower than that of the tabs. Moreover, due to the significant stiffening effects of the beam to the beam-end-connector, the specimen with beam height 145mm (2.3C2-B120-3T) failed at the upright other than the beam end. Particularly, connections with two tabs behaved similarly as boltless connections for the bolt located near the neutral axis of the section.

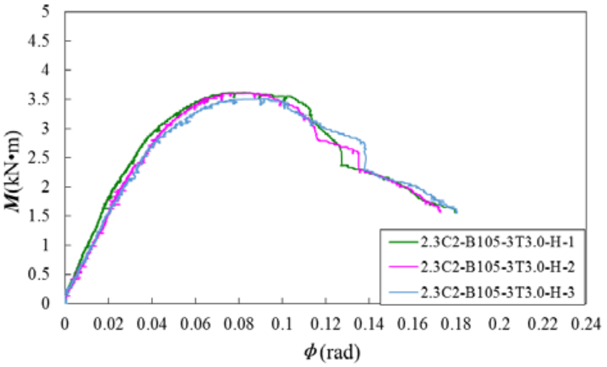
Table 2 shows the summary of monotonic tests results, including the stiffness, the ultimate moment capacity and the failure mode. The mean value of connection stiffness and moment capacity are also presented and employed to discuss the effects of various parameters, such as the upright thickness, the beam height and the number of tabs, on the connection behaviour. The stiffness is the gradient of the line from the origin to the half peak load point on the moment-rotation curves. The moment capacity is the maximum recorded applied moment.



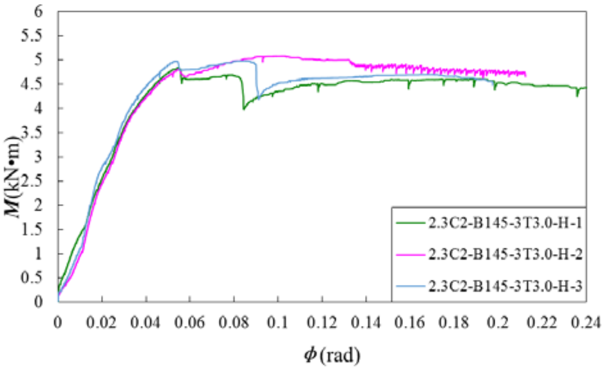
(a) 2.3C2-B120-3T



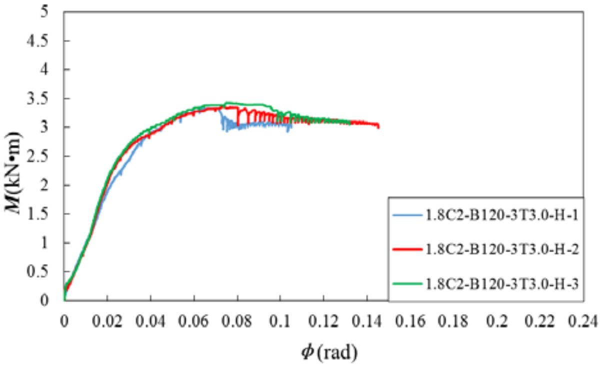
(b) 2.3C2-B120-3T-NB



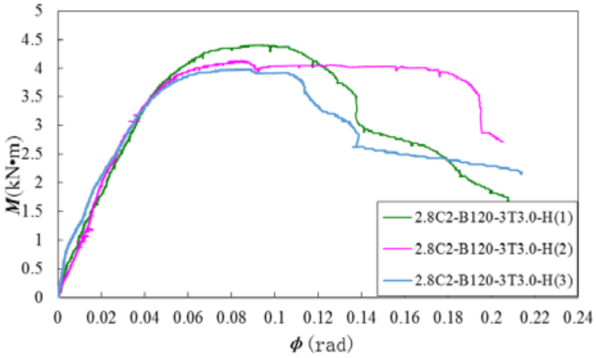
(c) 2.3C2-B105-3T



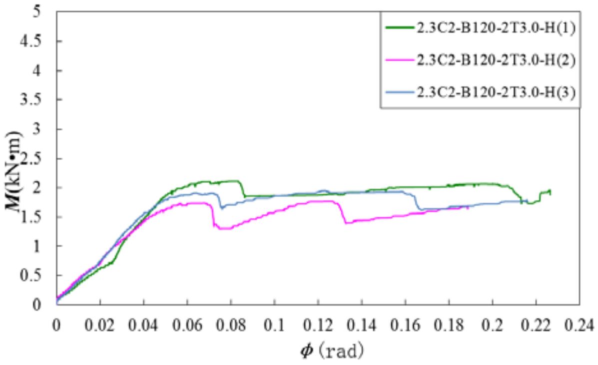
(d) 2.3C2-B145-3T



(e) 1.8C2-B120-3T



(f) 2.8C2-B120-3T



(g) 2.3C2-B120-2T

Figure 5 Moment-rotation curves

Table 2. Summary of monotonic tests results

Specimen	Test number	Stiffness (kN.m/rad)	mean	Moment capacity (kN.m)	mean	Failure mode
2.3C2-B105-3T	H(1)	89.4	79.3	3.62	3.58	T+BE
	H(2)	76.0		3.61		T+BE
	H(3)	72.4		3.51		T+BE
2.3C2-B120-3T-NB	H(1)	64.8	72.9	2.95	2.78	T
	H(2)	86.5		2.81		T
	H(3)	67.4		2.58		T
2.3C2-B120-3T	H(1)	83.3	92.8	3.99	4.00	T+BE
	H(2)	104.5		3.98		T+BE
	H(3)	90.7		4.02		T+BE
2.3C2-B145-3T	H(1)	139.7	133.8	4.84	4.97	T+C
	H(2)	121.2		5.08		T+C
	H(3)	140.6		4.98		T+C
1.8C2-B120-3T	H(1)	96.5	101.2	3.33	3.37	C
	H(2)	102.6		3.36		C
	H(3)	104.5		3.43		C
2.8C2-B120-3T	H(1)	87.2	98.7	4.40	4.17	T+BE
	H(2)	99.7		4.13		T+BE
	H(3)	109.2		3.98		T+BE
2.3C2-B120-2T	H(1)	37.8	37.67	2.11	1.94	T
	H(2)	37.4		1.77		T
	H(3)	37.8		1.95		T

Notes: H(1), H(2) and H(3) refer to the number of identical tests.

Discussion of test results

Comparison between connections with and without bolts

The comparison between the specimens “2.3C2-B120-3T” and “2.3C2-B120-3T-NB” demonstrates the effect of bolts on the behaviour of steel storage beam-to-upright connections. It can be seen from Table 2 (the first two groups), compared with boltless connections with the same upright thickness of 2.3mm, beam height 120mm and tab number of 3, the connections with bolts considerably enhance the rotational stiffness and the ultimate moment capacity by 9% and 29%, respectively. Boltless connections fail abruptly for tab crack or tearing of the upright. Whereas for bolted connections the moment resistance is provided by the bolt in shear and by the upright in compression after the tab crack. Therefore, the bolted connections generally behave better in ductility.

Effects of the beam height

As illustrated in Table 2, the beam height has a considerable influence on the flexural behaviour of the bolted connections. If we compare the specimens with the same upright “2.3C2” and beam-end-connector “3T”, the connection stiffness and the ultimate moment capacity are found to be continuously increased with the beam height increased from 105mm to 120mm to 145mm.

Effects of the upright thickness

The influence of the upright thickness on the flexural behaviour of the bolted connections can be analysed from the comparisons between “1.8C2-B120-3T”, “2.3C2-B120-3T” and “2.8C2-B120-3T”. As shown in Table 2, with increasing the upright thickness from 1.8mm to 2.8mm, the ultimate moment capacity of the bolted connections was increased by 23.7% as the transition from upright buckling to beam end failure. However, the connection stiffness slightly fluctuated with the increase of the upright thickness.

Effects of the tab numbers

Tab numbers relating to the depth of the beam-end-connector significantly influences the behaviour of bolted connections. Compared with the specimen “2.3C2-B120-2T”, the stiffness and the ultimate moment capacity of the specimen “2.3C2-B120-3T” was dramatically increased by 150% and 106% separately, as shown in Table 2.

Summary and conclusions

This paper has presented the experimental investigation into the flexural behaviour of steel storage rack beam-to-upright connections with bolts. The results of twenty-one individual experimental tests have been provided, including the moment-rotation curves, the stiffness, the ultimate moment capacity and the failure modes. Comparisons between connections with and without bolts have also been carried out in this paper. The influences of crucial parameters, such as the beam height, the thickness of the upright and the tab numbers, on the connection behaviour have been highlighted. Some important conclusions drawn from the present study are summarised:

1. The failure modes of steel storage rack beam-to-upright connections are classified into three basic types: tab crack (T), beam end failure (BE) and upright buckling (C). The combination of these failure modes are generally observed in tests. The failure modes of bolted connections are determined by relative thickness between the upright and the beam-end-connector, as well as the relative height between the beam and the beam-end-connector.

2. Compared with boltless connections, the beam-to-upright bolted connections have a considerably higher value of the stiffness and the moment capacity. In order to increase the structural stability, the bolted connections are considered to be an alternative beam-to-upright connection in steel storage racks.

3. The beam height and tab number have a significant impact on the stiffness

of bolted connections, while the influence of the upright thickness on the connection stiffness is limited. The ultimate moment capacity of connections are increased with increasing the beam height, the upright thickness and/or the tab numbers. Therefore, one of the critical issues in rack structures design is to choose an appropriate beam-to-upright connection.

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