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ORIGINAL RESEARCH

Cold-formed steel pallet rack connection: an experimental study

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Abstract Industrial pallet rack systems are made up of three-dimensional structural arrangement using cold-formed steel members. The rack columns (upright) have perforations at prescribed intervals to facilitate the assemblage of beams with end connections. The tabs are used as connections which are engaged into the perforations and are in particular, highly semi-rigid in nature. Due to the diversity of rack systems, connecting member's stiffness and strength, it is almost impossible to develop a generalised model for analytical predication of the connection stiffness. This paper describes the beam–column connection tests carried out on a commercially available pallet rack system by adopting single cantilever test set-up. Thirty-five sets of combinations are identified based on the variation in upright profile and thickness, depth of beam and the connector to study the connection stiffness. Three tests were performed for each set to bring in uniformity in the result taking the total number of tests to 105. A full range parametric study is carried out to understand the influence of above said parameters on moment–rotation behaviour and the joint stiffness. The experimental results showed that an improved performance of the joint connection is achieved using connectors with more number of tabs, greater thickness and improved profile of the upright and larger depth of the beam.

Keywords Storage rack systems · Pallet rack connections · Beam–column · Upright · Moment–rotation behaviour · Joint stiffness

Introduction

Industrial warehouse consumes large volumes of cold-formed steel in the form of storage racks. Variety of rack structures is available like pallet rack, drive-in, drive through rack etc. Pallet rack systems are used for relatively low density of storage or in situations where all goods can be accessible at all time, with efficient utilization of floor space compared to other type of storage system. A typical pallet rack system is shown in Fig. 1. The upright (column) frames act as vertical load carrying element; the horizontal beams get support from column frames, which are perpendicular to planes of the column. The goods are usually stored on pallets made of wood, metal or plastic which are placed by means of fork lift trucks upon the beams. The connections used in the pallet rack system are generally boltless semi-rigid connection. They are classified as boltless connection due to the beam end connector and use of tab connector, which get engaged based on perforation pitch of the upright. The tabs act as an integral part of the beam end connector, since the tabs are formed and punched out of the beam end connector. The semi-rigid behaviour is due to the distortion of upright-walls, tearing of upright perforation and distortion of beam end connector. Performance of a rack system depends on the efficiency of beam end connector. The beam end connector provides support to the beam and in unbraced racks; they are the only source of stiffness required for down aisle stability. The racks are not braced in down aisle direction for

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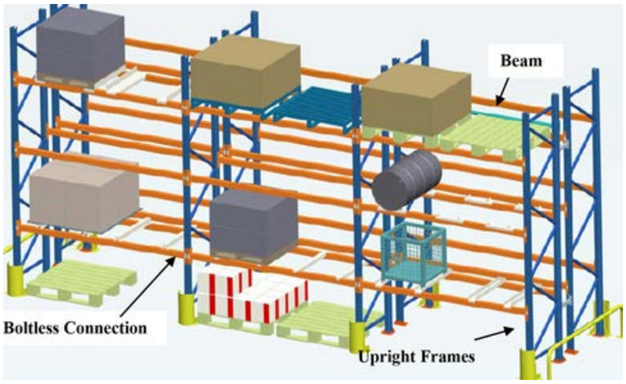

Fig. 1 Pallet rack storage system

practical reasons. Thus, the beam end connector is a critical component in ensuring the overall sway stability of the rack frame.

Literature review

The study on joint connection rigidity dates back to 1930s both at experimental and analytical front. But the studies on joint connection for cold-formed steel particularly on pallet rack system are only decade old. The beam–column connection tests are usually done to determine the relationship of the moment '*M*' at the joint—with the angle 'θ' between the column and the connecting beam. Lewis (1991) provided a simple design approach to ensure stability of pallet rack structures and to include the effect that the form of the moment–rotation characteristics has on the type of stability exhibited by the system.

Markazi et al. (1995) have carried out tests on four different commercially available beam end connectors to determine the parameters governing an efficient beam end connector design. A theoretical investigation was also carried out to estimate the influence of the flexibility of beam and the column used in the tests on the stiffnesses determined experimentally. Bernuzzi and Castiglioni (2001) have suggested that due to large variation in of beam end connectors, the analytical prediction of stiffness and strength of the connector is not practical and the major International rack design codes recommend experiments to determine the properties. Aguirre (2004) presented experimental findings about the beam–column connection under static and cyclic loads. The similarity of the static and cyclic failure modes indicate that the failure load is controlled entirely by the connecting elements. Bajoria and Talikoti (2006) have conducted tests to determine the flexibility of beam-to-column connectors used in conventional pallet racking systems by cantilever and double cantilever test set-up. A full-scale frame test was also carried out to verify the results. Due to the better representation of shear to moment ratio in an actual frame by double cantilever set-up, it is found to be superior to conventional single cantilever test. Harris (2006) has found that the test set-ups in the International code for rack testing are very similar, except that there is marginal difference in the test set-ups dimensions, transducers position and procedure. Prabha et al. (2010] have proposed two analytical models; the polynomial model based on Frye John and Morris (1975) procedure and the power model for cold-formed boltless semi-rigid pallet rack connections by conducting 18 experiments. The proposed polynomial model is found to predict the initial stiffness of the tested connections reasonably well and will be useful for the linear design space. The power model is capable of predicting the ultimate capacity of the connection.

A review of existing literature throws light into the area of research reported on the cold-formed pallet rack connections. On the other hand the usage of rack systems is growing across the globe; there is a strong need to experimentally evaluate the deformational characteristics of semi-rigid pallet rack connection. The purpose of this study is to understand the influence of parameters like beam size to which end connector is welded, depth of the connector, profile and the thickness of upright on the performance of the connection. Two beam end connector test set-up alternatives are proposed by the RMI (2008), AS:4084 (1993) and FEM (1998), the choice of the test set-up being the responsibility of the designer. However, since there is no design procedure available in arriving at the joint stiffness, only one test set-up is now proposed by the recent EN:15512 (2009) which is adopted in this study.

Experimental investigation

Adequate design procedures are not available for the perforated sections used in industrial racking and hence design has to be carried out based on the results of experiments conducted on members and/or the assemblies. The design specifications of international standards such as Rack Manufacturers Institute (RMI 2008) and European Standard EN: 15512 (2009) recognize the importance of investigating individual component characteristics, and they have almost similar approach to understand the component behavior. The purpose of the present experimental program is to investigate the semi-rigid characteristics of pallet rack connection by varying the profile and thickness of upright and depth of beam end connectors. The parameters varied are as follows: profile of the upright, thickness of the upright, depth of the beam and the depth of connector.

Specimen details

A total of 105 tests were carried out, composed of 3 trials of 35 variants which are distinguished by two types of upright profiles, four different upright thicknesses, seven different beam depths and three different beam end connector depth. Two types of upright profiles (profile A and B) are used and their cross section is given in Fig. 2. The details of the upright section are given in Table 1. The height of the upright is kept constant as 700 mm. The profile A upright has two different thicknesses, 1.6 and 1.8 mm and the profile B upright has three different thicknesses 1.8, 2.0 and 2.5 mm. The profile A upright has small intermediate stiffener (small trapezoid) in the web and the profile B upright has large intermediate stiffener in the web. The cross section of beam and the end connector is given in Fig. 3. The detail of the beam section is given in Table 2. The length width and thickness of the beam is 600, 50 and 1.6 mm, respectively. The depths of the beams used are 75, 87.5, 100, 110, 125, 150 and 175 mm. The dimension details of the beam end connector are given in Table 3. The width and thickness of the end connector are 39.5 and 3.5 mm, respectively. The depth of the connector is varied as 150, 200 and 250 mm which accommodate 3, 4 and 5 tabs, respectively. A total of 35 sets of experiments were identified and each set of experiment is given a specific specimen ID which is listed in Table 4. For example, the specimen ID 'A-1.8UT-4L-100BD' means where 'A' indicates the profile of upright, 1.8UT represents the upright thickness as 1.8 mm, 4L represents the number of tabs as 4 and 100 BD represents the depth of beam as 100 mm.

Coupon test results

The RMI (2008) and EN 15512 (2009) codes recommend that the material properties of pallet rack sections to be accurately determined by means of tensile coupon test. Upright and the beam are manufactured using cold-formed steel, whereas the beam end connector is manufactured using hot-rolled steel due to its better weldable characteristics. Tensile coupon tests are performed in accordance with Indian standard IS:1608 1995. Three tension coupons are fabricated for upright and the beam end connector with various depths. The coupons are obtained from the start, middle and the end of mother coil and their respective material properties are obtained. The average yield stress f_y, ultimate stress f_u, and the final percentage elongation are obtained from stress–strain curves. The material properties of each component are given in Table 5.

According to EN 15512 2009, procedure is adopted to apply a correction to the failure load or failure moment due to variations in the yield stress of the material and the thickness of the test specimen. The correction factor is always <1. The correction factor C_m is calculated as follows:

$$C_m = ((f_y/f_t)^{\alpha}(t/t_t))$$

where f_t is the observed yield stress for the relevant component, f_y is the nominal yield stress for the relevant component, t_t is the observed thickness for the relevant component, t is the design thickness for the relevant component, $\alpha = 0$ when $f_y > f_t$, $\alpha = 1$ when $f_y < f_t$.

The correction factor corresponding to upright and lip connector (Table 6) was applied to the combination of the connection and the corrected moment–rotation curve was generated.

Test set-up

Single cantilever test set-up is adopted in the present study and its schematic representation is given in Fig. 4. The upright of height 700 mm is placed on a rigid support base. The upright is connected to a relatively stiff testing frame at two points using bolts with a clear distance of 500 mm. Two plates are kept on both sides

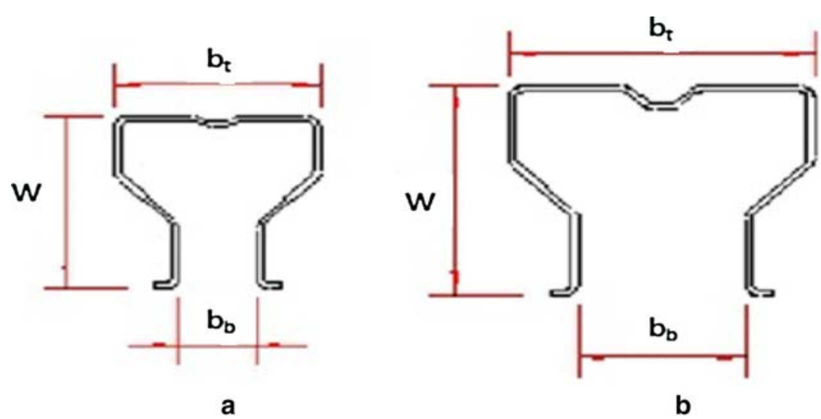

Fig. 2 Cross-section of upright profiles. **a** Profile A. **b** Profile B

Table 1 Details of upright section

S. no	Profile	Thickness t (mm)	Flange Width b_t (mm)	Opening b_b (mm)	Web w (mm)
1	A	1.6	80	30	80
2	A	1.8	80	30	80
3	B	1.8	110	60	90
4	B	2.0	110	60	90
5	B	2.5	110	60	90

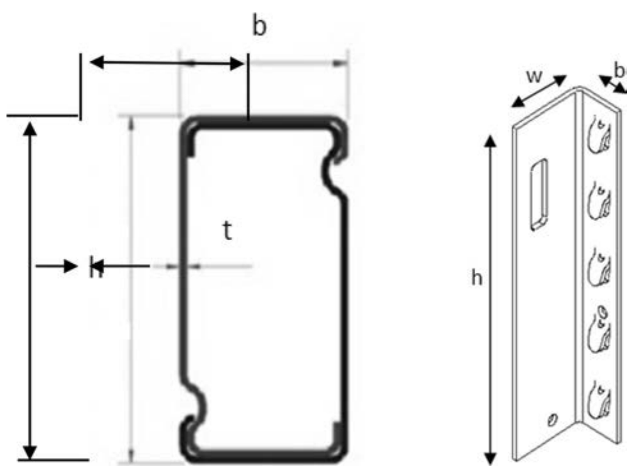

Fig. 3 Cross section of beam and the end connector

Table 2 Details of beam section

S. no	Width b (mm)	Depth h (mm)	Thickness t (mm)
1	50	75	1.6
2	50	87.5	1.6
3	50	100	1.6
4	50	110	1.6
5	50	125	1.6
6	50	150	1.6
7	50	175	1.6

of the bolt so as to avoid the contact of the upright with the reaction frame. The beam end connector with tabs is engaged into the perforations of the upright. The free end of the beam is constrained by lateral restraints to prevent the sideways movement and twisting of the beam end while loading. The full length of the beam is 600 mm and the load is applied at a distance of 400 mm from the face of the upright as shown in Fig. 5. The beam end

Table 4 Identified specimens

Set No	Specimen ID	Set No	Specimen ID
1	A-1.6UT-3L-75 BD	19	B-2.0UT-4L-110 BD
2	A-1.8UT-3L-75 BD	20	B-2.5UT-4L-110 BD
3	B-1.8UT-3L-75 BD	21	A-1.6UT-4L-125 BD
4	B-2.0UT-3L-75 BD	22	A-1.8UT-4L-125 BD
5	B-2.5UT-3L-75 BD	23	B-1.8UT-4L-125 BD
6	A-1.6UT-4L-87.5 BD	24	B-2.0UT-4L-125 BD
7	A-1.8UT-4L-87.5 BD	25	B-2.5UT-4L-125 BD
8	B-1.8UT-4L-87.5 BD	26	A-1.6UT-5L-150 BD
9	B-2.0UT-4L-87.5 BD	27	A-1.8UT-5L-150 BD
10	B-2.5UT-4L-87.5 BD	28	B-1.8UT-5L-150 BD
11	A-1.6UT-4L-100 BD	29	B-2.0UT-5L-150 BD
12	A-1.8UT-4L-100 BD	30	B-2.5UT-5L-150 BD
13	B-1.8UT-4L-100 BD	31	A-1.6UT-5L-175 BD
14	B-2.0UT-4L-100 BD	32	A-1.8UT-5L-175 BD
15	B-2.5UT-4L-100 BD	33	B-1.8UT-5L-175 BD
16	A-1.6UT-4L-110 BD	34	B-2.0UT-5L-175 BD
17	A-1.8UT-4L-110 BD	35	B-2.5UT-5L-175 BD
18	B-1.8UT-4L-110 BD	No of sets = 35	

connector is down welded at a distance of 40 mm from the top of beam in the tension side and is kept constant for all the test combinations. Locking pin is inserted in the middle position and the purpose is to keep the connector and the upright in position and to prevent any accidental uplift. The inclinometer is placed as close to the connection to record precisely the initial slackness of the tab connector. The inclinometer and the load cell are connected to a computer-assisted data logging system to monitor the real-time response during the test. Initially, 10 % of the anticipated failure load is applied as a preload to bed in the components. Later, the actual load is applied at small increments till failure of the connection.

Table 3 Details of the beam end Connector

S. no	No. of tabs	Breadth b (mm)	Width w (mm)	Depth h (mm)	Thickness t (mm)
1	3	39.5	64	150	3.5
2	4	39.5	64	200	3.5
3	5	39.5	64	250	3.5

Table 5 Material properties of the component

S. no	Component	Yield stress (MPa)	Ultimate stress (MPa)	Elongation %
1	Upright profile A	418	484	28
		407	476	30
		413	479	32
2	Upright profile B	404	481	28
		409	469	28
		411	449	32
3	5 tab connector	406	473	29
		415	477	30
4	4 tab connector	372	469	28
		375	481	28
5	3 tab connector	404	469	28
		409	481	28

Table 6 Correction factor based on yield stress and thickness

S. no	Component	Observed yield stress f_t (MPa)	Nominal yield stress f_y (MPa)	Observed thickness t (mm)	Nominal thickness t_t (mm)	Correction factor C_m
1	Upright profile A	418	355	1.65	1.6	0.82
		407	355	1.65	1.6	0.85
		413	355	1.85	1.8	0.84
2	Upright profile B	404	355	1.81	1.8	0.87
		409	355	2.00	2.0	0.87
		411	355	2.62	2.5	0.82
3	5 tab connector	406	355	3.48	3.5	0.88
		415	355	3.48	3.5	0.86
4	4 tab connector	372	355	3.51	3.5	0.95
		375	355	3.51	3.5	0.94
5	3 tab connector	404	355	3.49	3.5	0.88
		409	355	3.49	3.5	0.87

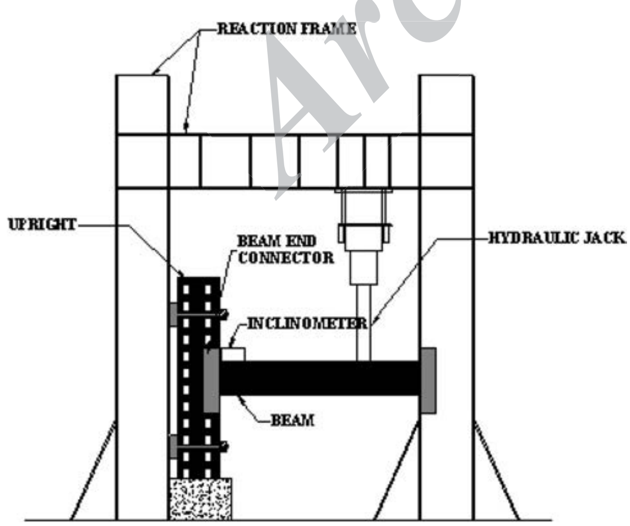

Fig. 4 Schematic diagram of the test set-up

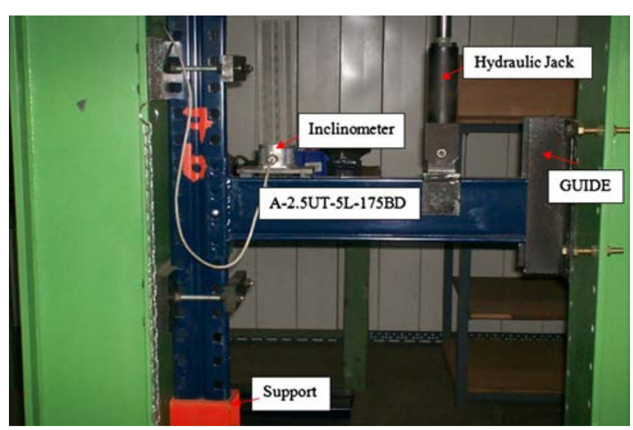

Fig. 5 Single cantilever test set-up

Experimental results

From the recorded data, the moment–rotation behaviour of the connection is plotted for all the specimens. Three identical tests were done for each set to determine the spread of the results. The results were used to determine the ultimate moment of resistance and joint stiffness of the beam end connector. Behaviour exhibited by all the connections is found to be non-linear. The moment–rotation behaviour consists of bilinear curves. The rotational stiffness is taken as the slope of line passing through the origin which isolates equal areas between it and the experimental curve, below the design moment corrected for yield stress and thickness as shown in the Fig. 6. The kink observed in the moment–rotation curve indicates the contact of the beam end connector with the face of upright in the compression side.

The failure of the different tab connectors are shown in Fig. 7. In all the experiments with upright thickness <2.5 mm, the failure is initiated by the tearing of upright web in the tension side. The beam end connector of depth 150 mm has 3 tabs and the failure is initiated by the first tab in the tension side tearing the column web. Whereas for the larger depth end connector with 4 tabs (200 mm depth) and 5 tabs (250 mm depth), the first two and three tabs initiated the failure. It is observed that for the specimens with higher upright thickness of 2.5 mm, the extent of damage caused by the tearing of upright web is found to be less. Due to the increase in the thickness of upright, the tabs in the beam end connector have undergone larger deformation due to the in plane moment. The distortion of upright web portion due to the tab impression is shown in Fig. 8. The ultimate moment failure load and the joint stiffness obtained for all the tests are given in Table 7. When the tab is not engaged properly with the upright, a larger initial rotation in the connection is observed, therefore, it is required to give an initial loading to make a proper engagement of the beam end connector to the upright.

Results and discussions

Effect of column thickness on the behaviour

The moment–rotation behaviour of the connection is plotted for the upright profile A with 3, 4 and 5 tab connectors in Figs. 9, 10, 11, respectively and for upright profile B with different connector depths in Figs. 12, 13, 14. One smooth curve was chosen in each combination of 3 trials and was compared.

For profile A upright with 3 tab connector

The profile A upright with 3 tab connector is tested with the beam depth of 75 mm. It is observed from Fig. 9, that with the increase in column thickness from 1.6 to 1.8 mm for a constant beam depth of 75 mm, there is an appreciable increase of 29 % in the joint stiffness and 23 % increase in the ultimate moment capacity.

For profile A upright with 4 tab connector

The profile A upright with 4 tab connector is tested with 4 different beam depths of 87.5, 100, 110 and 125 mm. From the M-θ plot shown in Fig. 10, with the increase in column thickness from 1.6 to 1.8 mm for a constant beam depth of 87.5 mm, there is a marginal increase of 7.65 % in the ultimate moment capacity, whereas the joint stiffness is found to increase by 27 %. For a constant beam depth of 100 mm, the increase in the ultimate moment capacity is found to be 18.9 % and the joint stiffness has increased by 8.53 %. Similarly, for the next higher beam depths of 110 and 125 mm, there is an increase in the ultimate moment capacity by 24.3 and 14 %, respectively and the joint stiffness increases by 7 % for beam depth of 110 mm and decreases by 5.65 % for beam depth of 125 mm.

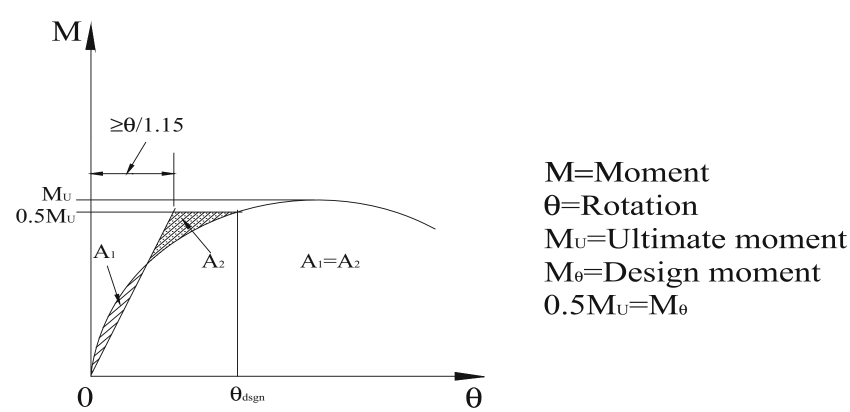

Fig. 6 Method to arrive at joint stiffness

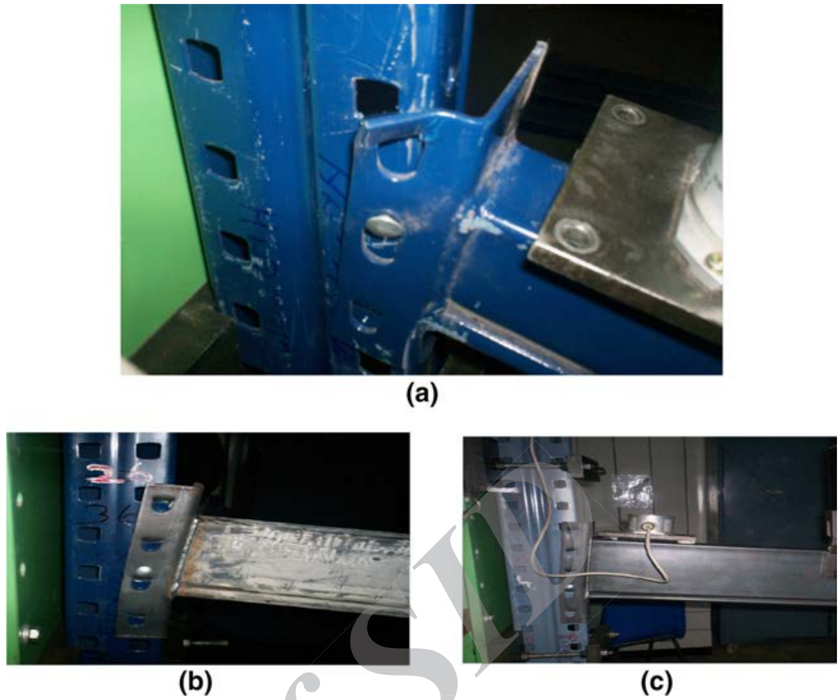

Fig. 7 Failure of the connector. **a** Three tab connector. **b** Four tab connector. **c** Five tab connector

Fig. 8 Damage of the upright

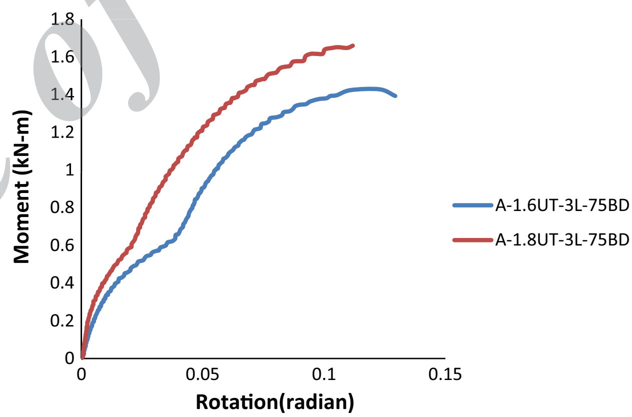

Fig. 9 M-θ curves for profile A upright with 3 tab connector

For profile A upright with 5 tab connector

Totally four tests are conducted on profile A uprights with 5 tab connector which consists of two different beam depths of 150 and 175 mm. From the M-θ plot shown in Fig. 11, with the increase in column thickness from 1.6 to 1.8 mm for a constant beam depth of 150 mm, the ultimate moment capacity increases by 16.4 %, whereas the joint stiffness is found to decrease by 36.89 %. For a constant beam depth of 175 mm, the increase in the ultimate moment capacity is found to be 41.4 % and there is an enormous increase in the joint stiffness by 71 %.

For profile B upright with 3 tab connector

The profile B upright with 3 tab connector has three different thicknesses of 1.8, 2.0 and 2.5 mm and beam depth of 75 mm. With the increase in column thickness from 1.8 to 2.0 mm for a constant beam depth of 75 mm there is a marginal increase of 11 % in the ultimate moment capacity. Further increase in the thickness to 2.5 mm has

Table 7 Test results

Set no.	Test no.	Trials	Failure load (kN)	Avg. failure load (kN)	Ultimate moment capacity (kNm)	Avg. ultimate moment capacity (kNm)	Rotation at the ultimate moment (radians)	Stiffness (kNm/rad)	Avg. stiffness (kNm/rad)	Stiffness variation (%)
1	A-1.6UT-3L-75 BD	1	3.10	3.31	1.240	1.323	0.098	18.48	19.75	12.5
		2	3.26		1.303		0.104	19.99		
		3	3.57		1.428		0.123	20.79		
2	A-1.8UT-3L-75 BD	1	4.11	4.07	1.644	1.628	0.112	25.85	25.49	6.87
		2	4.15		1.660		0.118	26.15		
		3	3.95		1.581		0.123	24.47		
3	B-1.8UT-3L-75 BD	1	3.81	3.90	1.523	1.560	0.094	25.31	26.76	11.3
		2	4.02		1.609		0.100	26.79		
		3	3.88		1.550		0.076	28.17		
4	B-2.0UT-3L-75 BD	1	4.34	4.33	1.735	1.730	0.114	23.06	24.35	9.2
		2	4.39		1.754		0.102	25.19		
		3	4.26		1.703		0.102	24.79		
5	B-2.5UT-3L-75 BD	1	4.41	4.45	1.76	1.782	0.098	26.14	28.07	64.6
		2	4.51		1.805		0.093	36.13		
		3	4.45		1.782		0.115	21.95		
6	A-1.6UT-4L-87.5 BD	1	5.25	5.13	2.099	2.052	0.097	50.96	45.96	11.12s
		2	4.95		1.982		0.069	45.86		
		3	5.19		2.076		0.091	41.07		
7	A-1.8UT-4L-87.5 BD	1	5.15	5.52	2.060	2.209	0.073	49.73	58.51	35.25
		2	5.66		2.264		0.096	58.53		
		3	5.76		2.303		0.095	67.26		
8	B-1.8UT-4L-87.5 BD	1	5.41	5.51	2.162	2.202	0.089	50.25	51.72	5.9
		2	5.41		2.162		0.086	51.64		
		3	5.71		2.284		0.071	53.25		
9	B-2.0UT-4L-87.5 BD	1	5.96	5.89	2.386	2.355	0.108	40.67	43.30	19.08
		2	5.89		2.354		0.091	48.43		
		3	5.82		2.327		0.104	40.81		
10	B-2.5UT-4L-87.5 BD	1	6.77	6.67	2.708	2.668	0.104	57.06	54.28	9.79
		2	6.76		2.704		0.107	53.82		
		3	6.48		2.594		0.101	51.97		
11	A-1.6UT-4L-100 BD	1	5.40	5.27	2.158	2.107	0.087	46.93	44.56	18.43
		2	5.36		2.143		0.084	47.04		
		3	5.05		2.021		0.088	39.72		

Table 7 continued

Set no.	Test no.	Trials	Failure load (kN)	Avg. failure load (kN)	Ultimate moment capacity (kNm)	Avg. ultimate moment capacity (kNm)	Rotation at the ultimate moment (radians)	Stiffness (kNm/rad)	Avg. stiffness (kNm/rad)	Stiffness variation (%)
12	A-1.8UT-4L-100 BD	1	6.30	6.27	2.519	2.507	0.102	47.19	48.36	20.22
		2	6.14		2.457		0.091	44.46		
		3	6.37		2.547		0.088	53.45		
13	B-1.8UT-4L-100 BD	1	6.44	6.33	2.574	2.531	0.114	53.90	54.46	4.46
		2	6.11		2.445		0.092	53.54		
		3	6.44		2.574		0.089	55.93		
14	B-2.0UT-4L-100 BD	1	6.51	6.51	2.606	2.606	0.106	46.50	51.60	17.90
		2	6.59		2.638		0.104	54.84		
		3	6.44		2.574		0.099	53.47		
15	B-2.5UT-4L-100 BD	1	7.69	7.78	3.077	3.115	0.097	66.01	69.54	16.54
		2	7.58		3.033		0.089	65.86		
		3	8.09		3.237		0.104	76.75		
16	A-1.6UT-4L-110 BD	1	5.61	6.09	2.245	2.437	0.072	57.46	96.22	153.44
		2	6.15		2.460		0.056	85.55		
		3	6.51		2.606		0.060	145.63		
17	A-1.8UT-4L-110 BD	1	7.21	7.34	2.884	2.937	0.091	74.14	76.54	11.6
		2	7.88		3.151		0.096	82.01		
		3	6.95		2.778		0.087	73.46		
18	B-1.8UT-4L-110 BD	1	6.31	6.56	2.523	2.626	0.067	71.82	75.17	16.56
		2	6.80		2.719		0.075	82.72		
		3	6.59		2.637		0.073	70.97		
19	B-2.0UT-4L-110 BD	1	6.51	6.65	2.606	2.662	0.063	71.17	77.69	23.22
		2	6.69		2.676		0.061	87.70		
		3	6.76		2.704		0.082	74.21		
20	B-2.5UT-4L-110 BD	1	6.95	7.02	2.778	2.807	0.062	85.20	90.55	40.16
		2	6.91		2.763		0.060	108.81		
		3	7.20		2.880		0.069	77.63		
21	A-1.6UT-4L-125 BD	1	5.49	5.56	2.197	2.223	0.072	52.65	59.45	21.88
		2	5.11		2.044		0.047	61.52		
		3	6.07		2.429		0.076	64.17		
22	A-1.8UT-4L-125 BD	1	6.42	6.34	2.566	2.536	0.071	55.34	56.27	3.38
		2	6.48		2.594		0.071	56.26		
		3	6.12		2.449		0.072	57.21		

Table 7 continued

Set no.	Test no.	Trials	Failure load (kN)	Avg. failure load (kN)	Ultimate moment capacity (kNm)	Avg. ultimate moment capacity (kNm)	Rotation at the ultimate moment (radians)	Stiffness (kNm/rad)	Avg. stiffness (kNm/rad)	Stiffness variation (%)
23	B-1.8UT-4L-125 BD	1	6.63	6.92	2.653	2.770	0.069	77.03	78.34	7.05
		2	6.87		2.747		0.068	81.69		
		3	7.28		2.912		0.071	76.31		
24	B-2.0UT-4L-125 BD	1	7.15	7.23	2.861	2.892	0.070	78.73	85.04	34.24
		2	7.56		3.025		0.071	101.08		
		3	6.98		2.790		0.071	75.30		
25	B-2.5UT-4L-125 BD	1	7.35	7.64	2.939	3.056	0.064	102.72	105.52	6.66
		2	7.66		3.064		0.061	104.26		
		3	7.92		3.167		0.069	109.57		
26	A-1.6UT-5L-150 BD	1	8.33	6.80	3.332	2.721	0.059	192.62	222.09	60.60
		2	5.86		2.343		0.038	291.89		
		3	6.22		2.488		0.043	181.75		
27	A-1.8UT-5L-150 BD	1	9.72	8.46	3.889	3.388	0.059	157.76	136.74	26.61
		2	8.14		3.257		0.056	127.86		
		3	7.54		3.018		0.056	124.60		
28	B-1.8UT-5L-150 BD	1	9.65	9.65	3.861	3.863	0.069	106.96	98.84	21.86
		2	9.64		3.857		0.079	87.77		
		3	9.68		3.873		0.056	101.80		
29	B-2.0UT-5L-150 BD	1	10.43	10.06	4.171	4.023	0.068	114.57	108.60	12.19
		2	9.66		3.865		0.056	102.12		
		3	10.09		4.034		0.080	109.11		
30	B-2.5UT-5L-150 BD	1	10.97	11.24	4.387	4.496	0.055	151.20	133.25	24.20
		2	11.16		4.466		0.063	126.80		
		3	11.60		4.638		0.069	121.74		
31	A-1.6UT-5L-175 BD	1	6.57	6.91	2.629	2.766	0.035	126.94	117.34	20.40
		2	7.39		2.955		0.051	105.40		
		3	6.79		2.715		0.034	119.67		
32	A-1.8UT-5L-175 BD	1	10.07	9.78	4.026	3.912	0.053	211.18	200.49	68.70
		2	10.21		4.085		0.050	145.25		
		3	9.06		3.626		0.035	245.03		
33	B-1.8UT-5L-175 BD	1	10.68	10.75	4.273	4.303	0.081	118.87	126.56	10.70
		2	10.92		4.367		0.073	129.22		
		3	10.67		4.269		0.077	131.60		

Table 7 continued

Set no.	Test no.	Trials	Failure load (kN)	Avg. failure load (kN)	Ultimate moment capacity (kNm)	Avg. ultimate moment capacity (kNm)	Rotation at the ultimate moment (radians)	Stiffness (kNm/rad)	Avg. stiffness (kNm/rad)	Stiffness variation (%)
34	B-2.0UT-5L-175 BD	1	11.53	11.52	4.611	4.609	0.064	125.74	117.39	12.26
		2	11.45		4.579		0.074	112.00		
		3	11.60		4.638		0.072	114.45		
35	B-2.5UT-5L-175 BD	1	12.74	13.01	5.097	5.20	0.048	179.58	174.03	20.95
		2	13.22		5.287		0.051	187.50		
		3	13.08		5.230		0.061	155.02		

resulted in 14.2 % increase in the moment capacity. But there is only a slight increase in the joint stiffness by 4 % with the increase in upright thickness.

For profile B upright with 4 tab connector

The profile B upright with 4 tab connector is tested with 4 different beam depths of 87.5, 100, 110 and 125 mm. With the increase in column thickness from 1.8 to 2.0 mm for a constant beam depth of 87.5 mm, there is a marginal increase of 7 % in the ultimate moment capacity and 19.4 % decrease in the joint stiffness. Further increase in the thickness to 2.5 mm has resulted in 21 % increase in the moment capacity and only 4.9 % increase in the joint stiffness. For 100 mm beam depth there is no appreciable change in the moment capacity, but the joint stiffness reduces by 5.5 %. Further increase in the thickness to 2.5 mm has resulted in an increase of 23 % on the ultimate moment capacity and the joint stiffness increases by 27 %. With the increase in column thickness from 1.8 to 2.0 mm for a constant beam depth of 110 mm there is no appreciable increase in the capacity and joint stiffness. Whereas further increase in thickness resulted in 7 and 20 % increase in moment capacity and joint stiffness, respectively. For a constant beam depth of 125 mm, with the increase in thickness from 1.8 to 2.0 mm there is a slight increase in the capacity by 4.5 % and joint stiffness by 8.55 % and further increase in the thickness to 2.5 mm resulted in 10 and 35 % increase in the capacity and joint stiffness, respectively.

For profile B upright with 5 tab connector

Totally, six set of tests are conducted on profile B uprights with 5 tab connector which consists of two different beam depths of 150 and 175 mm. With the increase in column thickness from 1.8 to 2.0 mm for a constant beam depth of 150 mm, the ultimate moment capacity increases by 4.14 %, whereas the joint stiffness is found to increase by 10 %. For upright thickness of 2.5 mm, the ultimate moment is increased by 16.38 % and the joint stiffness is increased by 34.8 %. For a constant beam depth of 175 mm, the increase in thickness from 1.8 to 2.5 mm resulted in the increase in ultimate moment capacity in the range of 7–20 % and there is an appreciable increase in the joint stiffness by 7–37 %.

Effect of beam depth on the behaviour

For profile A upright with 4 tab and 5 tab connector

For profile A upright with constant thickness of 1.6 mm with 4 tab connectors, when increasing the beam depth

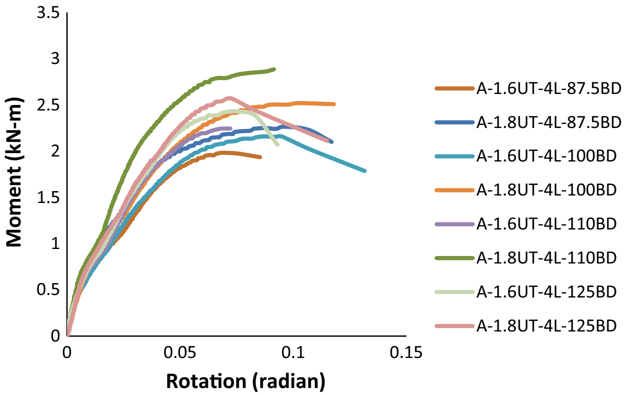

Fig. 10 M-θ curves for profile A upright with 4 tab connector

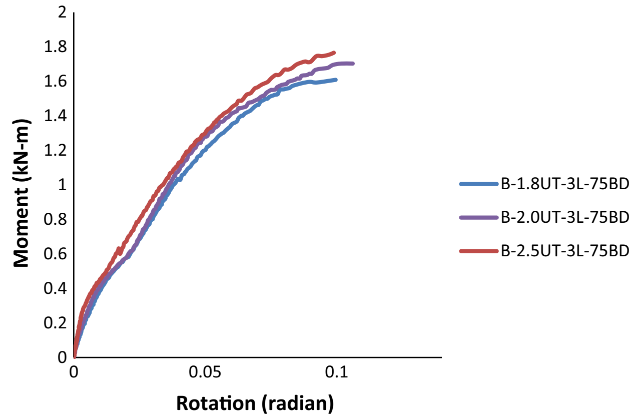

Fig. 12 M-θ curves for profile B upright with 3 tab connector

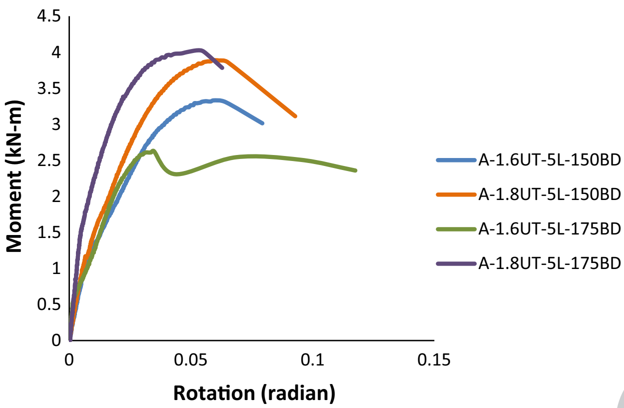

Fig. 11 M-θ curves for profile A upright with 5 tab connector

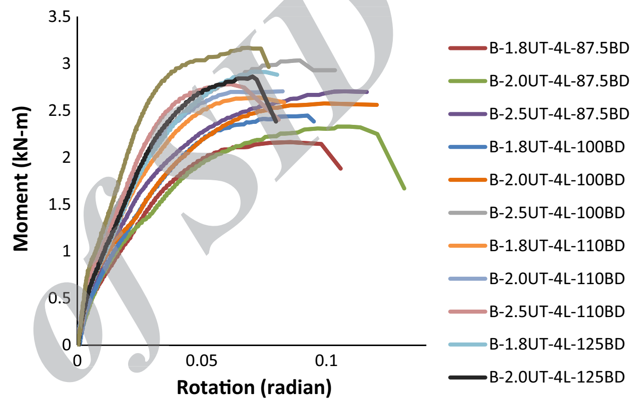

Fig. 13 M-θ curves for profile B upright with 4 tab connector

from 87.5 to 110 mm, the ultimate moment increases in the range of 3–14 %. For the increase in the depth of 100 mm, the joint stiffness remained same; for the next higher depth of 110 mm, the joint stiffness increases appreciably by 55 %. Interestingly there is a decrease in the ultimate moment capacity and joint stiffness by 5 and 20 %, respectively when the beam depth increases from 110 to 125 mm. Similar trend is observed for profile A upright with 1.8 mm thickness. For profile A upright with constant thickness of 1.6 mm with 5 tab connector, the moment capacity and joint stiffness reduces for the increase in beam depth from 150 to 175 mm. But for 1.8 mm upright with 5 tab connector, the moment capacity and the joint stiffness is observed to be increasing for beam depth from 150 to 175 mm.

For profile B upright with 4 tab and 5 tab connector

For profile B upright with constant thickness of 1.8 mm with 4 tab connectors, with the increase in beam depth from 87.5 to 125 mm, the moment capacity increases by 14–25 % and joint stiffness increases by 5–52 %. For the upright thicknesses 2.0 and 2.5 mm, the increase in beam depth from 87.5 to 125 mm causes 1.9 times increase in the joint stiffness with a 22 % increase in the moment capacity. For profile B upright with thicknesses of 1.8, 2.0 and 2.5 mm and with 5 tab connector, with the increase in depth from 150 to 175 mm, the moment capacity increases marginally by 11–15 % and the joint stiffness increases by 8–30 %.

Effect of upright profile on the behaviour

The effect of upright profile on the moment–rotation behaviour is discussed here. The profile A upright has a small intermediate stiffener in the web and profile B upright has a deep intermediate stiffener as shown in Fig. 2. Figures 15, 16, 17 show the comparison of moment–rotation curves plotted for 3, 4, 5 tab connector specimens, respectively with two different upright profiles. From Fig. 15, it is observed that for the 3 tab connector specimens with 75 mm beam depth, change in the upright profile has little influence on the moment–rotation behaviour. The similar trend is observed for the 4 tab connector specimens with the

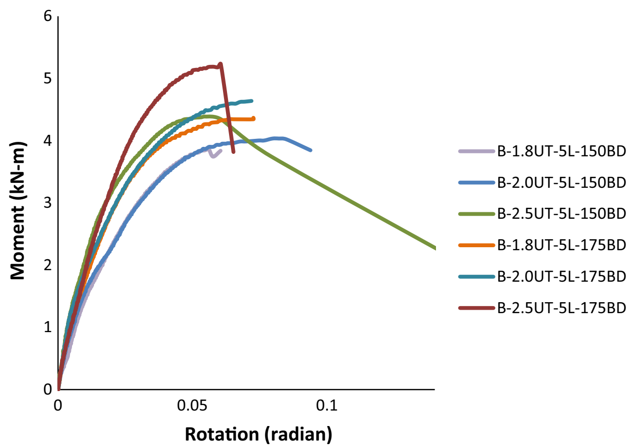

Fig. 14 M-θ curves for profile B upright with 5 tab connector

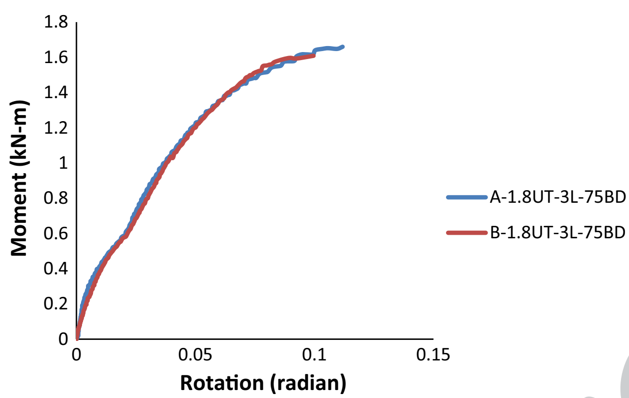

Fig. 15 Effect of upright profile on M-θ behaviour for specimens with 3 tab connector

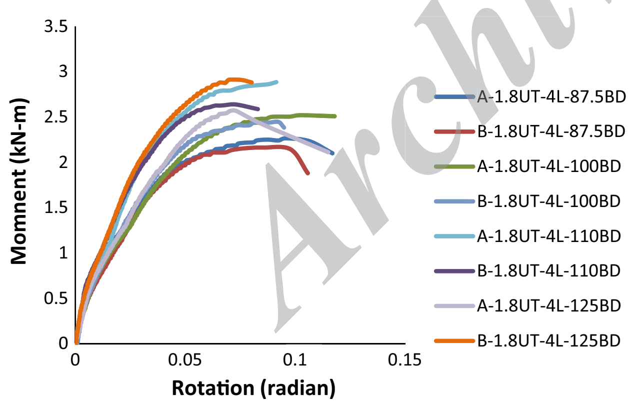

Fig. 16 Effect of upright profile on M-θ behaviour for specimens with 4 tab connector

beam depths 87.5 and 100 mm. But for the next higher beam depth of 110 mm, the moment capacity and the joint stiffness slightly reduces and for the specimens with beam depth of 125 mm, there is an increase in the joint stiffness by 39 % and the moment capacity by 9 %. For the 5 tab connector specimens with 150 mm beam depth, there is an

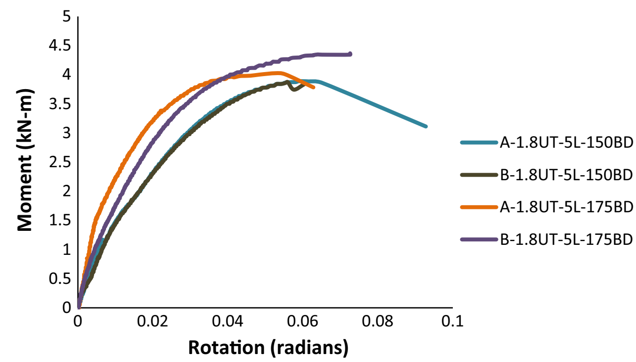

Fig. 17 Effect of upright profile on M-θ behaviour for specimens with 5 tab connector

increase in moment capacity by 14 % whereas there is a reduction in joint stiffness by 38 %. In the case of beam depth of 175 mm, the same phenomenon is observed.

Conclusions

Boltless semi-rigid connections are used in the storage industry. An experimental study on the behaviour of beam–column joints in the pallet rack system is presented. A total of 105 tests were carried out, composed of 3 trials of 35 variants which are distinguished by two types of upright profiles, four different upright thicknesses, seven different beam depths and three different beam end connector depths. By examining the moment–rotation curves, ultimate moment capacity and the joint stiffness, the following conclusions are drawn.

1. The combination of 4 or 5 tab connector with increased thickness of upright and greater depth of beam resulted in greater stiffness and strength of the joint.
2. The design of the tab plays a vital role in the strength and stiffness; it is observed that due to the point contact of tab with the upright the stiffness is reduced to a greater extent. As an alternative, the tab could be designed as line contact there by increasing the stiffness of the joint. This may probably eliminate tearing failure of upright.
3. The extent of damage (tearing failure) suffered by the upright is more for the specimens with upright thickness <2.0 mm.
4. Based on the tests conducted on two selected upright profiles A and B with equal thickness, the profile B with larger intermediate stiffener has only marginal influence on the moment carrying capacity for beam depth <125 mm.

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