Determination of flexibility of beam-to-column connectors used in thin walled cold-formed steel pallet racking systems

K.M. Bajoria *, R.S. Talikoti

Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India

Abstract

This paper describes a new test to determine flexibility of beam-to-column connectors used in conventional pallet racking systems. In this study, two different ways were used to find the flexibility of a connector. The connector developed was tested using the conventional cantilever method [Bajoria, KM. Three dimensional progressive collapse of warehouse racking, PhD Thesis, University of Cambridge, UK 1986], and then also using a newly proposed double cantilever method. To verify the results obtained from both the tests, a full scale frame test was carried out. In the double cantilever test the connector is subjected to three types of forces namely moment, shear and the axial pull by the beams, thereby giving behavior close to practical usage of connectors. Non-linear finite element analysis of both the tests and also of the full scale test were carried out using ANSYS [ANSYS 7.0—User’s Manual, ANSYS Inc., 2005] software. The results obtained from the double cantilever test were found to match well with the full scale frame test. The experimental results and the finite element results are compared in this paper.

Keywords: Pallet racks; Beam-to-column joints; Semi-rigid frames; Connector; Joint response; Cold-formed steel; Flexibility; Frame test

1. Introduction

In storage racks, hook-in end connectors are used to make beam to column connections. The semi-rigid nature of this connection is primarily due to distortion of the column walls, tearing of the column perforation, and distortion of the beam end connector. The storage rack stability depends significantly on the behavior of this connection, and therefore, it is important to have a proper way of predicting it. Designs of these connections vary widely, making it impossible to develop a general analytic model. Instead, beam to column connection tests are usually done to determine the relationship of the moment at the joint $M$ and the change in angle between the column and the connecting beam $\theta$. A complete study is performed to find out the flexibility of the beam-column connector with experimental studies and this was followed by full scale frame test to compare the results obtained from the two tests. Finite element analyses of both the tests and also of full scale test was carried out using ANSYS [1] software. The experimental results along with finite element analysis are presented here in this paper.

In the past, researchers have investigated various different types of connectors used in pallet racking systems. Baldassino and Bernuzzi [3] have given the influence of beam-to-column joint modeling on the overall frame response in their numerical study. Bernuzzi, and Castiglioni [4] carried out some experiments on the behavior of flexible connections, when subjected to cyclic reversal loading and investigated the effect of joint performance on the overall frame response. Bolts, screws, blind rivets or cartridge fired pins are commonly used in joints between cold-formed sections or for steel sheet connections. Recent research, by Rogers and Hancock [9,10] have studied the extension of actual design specifications to high strength steel sheets. Dubina and Zaharia [6], by means of experimental tests and numerical simulations, have studied the rotational capacity of bolted joints between cold-formed C sections with the objective to use, in the design of latticed beams, the advantage of the semi-rigid behaviour of the joints. Fan et al. [7] have carried out numerical simulations using a finite element program with strong features in the non-linear computations with large inelastic strains and contact elements to improve our knowledge of the real behaviour of the joints.
The moment carrying capacity of the beam end connector was determined by a simple cantilever (beam-to-column connection) test Markazi et al. [8]. Tan et al. [11] have given a mathematical model to represent the connection behavior after carrying out experimental studies on the non-linear behavior of their connector.

There are many types of beam-end-connectors with different geometry of the connected members available in literature. The theoretical approaches to evaluate the performance of such joints are currently available only for few simple connectors. As a consequence, such type of connector design needs proper experimental evaluation and also numerical studies. In this paper, two such experimental set-ups are presented to find out the flexibility of the connector developed, which is verified by a full scale test.

2. Cantilever test

The experimental set-up used for this test is shown in Fig. 1. The column is fixed at both the ends, and a box section beam is connected to the column with the help of beam connector. The out-of-plane movement of the cantilever beam with connector is prevented by a using a side plate. Vertical load is applied at the free end of the beam in steps and the corresponding rotations of the beam and the column are calculated from observed deflections using the dial gauges for each load step. Moment acting on the connection is given as the product of applied load $P$ and the lever arm $d$. In the cantilever test, the connection stiffness $F$ is given as moment per unit rotation. The test and finite element results are compared in Fig. 8.

3. Double cantilever test set-up

Fig. 2 shows experimental set-up for double cantilever test. The ends of box section beams are pin connected using two vertical channel sections. The other two ends of beam are connected to the upright section using flexible connectors (Fig. 2). The load is applied in vertical direction gradually on the top of upright in a UTM, and the corresponding rotations of the beams were calculated from observed deflections of dial gauges.
gauge. The entire assembly was prevented from moving out-of-plane by using a side plate. Strain gauges were fixed on the inner face of the column near the slots to find the actual stresses coming on the upright. The test and finite element results are compared in Fig. 12.

4. Frame testing

Full scale frame testing is done to assess the behavior of all the components forming the frame with special emphasis on the beam to column connector developed. The aim is to assess the behavior of connector and continuity of the frame in actual conditions. The maximum load was limited to permissible values as per deflection criteria (of beam), moment capacity of the connector, and stress criteria of the beam and upright. The cross sections of column and box beam used are shown in Fig. 4. The frame is of two bay and two stories, braced together by cross bracings. The experimental set-up along with various strain gauge locations during the test is shown in Fig. 3. Total frame height is 3.0 m with each storey of 1.5 m, clear span of each bay is 2.7 m and bay width in transverse direction is 1.0 m (outer to outer). Bracings bolted to the upright are made of ‘C’ section. Four strain rosettes and twelve strain gauges (total of twenty-four points) were fixed on the beams and upright (see Fig. 3.). Generally in pallet racking systems the beam is loaded by four point loads. Hence, a four point load is applied in this test (see Fig. 3). MS plates of 3.15 mm thickness and 2.50 × 1.25 m size each weighing approximately 740 N are used for loading. Loading was done on bottom storey only. This kind of loading has advantage over conventional sand bag loading, with respect to better load distribution, accuracy and cleanliness. Total of 34 plates were used with 17 in each bay. The test and finite element analysis results are compared in Table 4.

5. Finite element modeling

5.1. Cantilever test

In order to study, the behavior of the connection, non-linear finite element analysis was performed using ANSYS [1]. A finite element model (Fig. 5) that best represents the behavior of the connection was developed. Geometry, boundary and loading conditions of the finite element model were made as close to the cantilever test as possible (Fig. 2). The column was fixed in all degrees of freedom at both the ends to represent the ends of the column that were welded to immovable supports. Contact surfaces were defined using CONTA173 element between the connector plate and the column to represent their interaction. The hook in connector was modeled by the use of SOLID43 element to provide connection between the connector and the column. The column and beam section were modeled using SHELL63 element. The material model was elastic–plastic with strain hardening capabilities and having the properties shown in Table 1. Properties of various finite elements used for the analysis are given in Table 2.

A concentrated load was applied at 900 mm. from the connection on the beam to represent the jack load. The load was gradually applied in steps and the rotation of the connector was monitored using four nodes as shown in Fig. 6. The total
Load applied here was equal to that applied during the test. The moment–rotation curve resulting from the finite element analysis and the physical test are compared in Fig. 8. The deformed shape in the finite element analysis with Von Mises stress is shown in Fig. 7.

5.2. Double cantilever test

The entire test assembly was modeled using ANSYS [1]. SHELL63 element was used to represent the column and the box beam section. Contact surfaces were defined using CONTA173 element between the connector plate and the column to represent their interaction. The hook in connector was modeled by the use of SOLID43 element to provide connection between the connector and the column. Geometry, boundary and loading conditions of the finite element model were made as close to the double cantilever test as possible (Fig. 2). The far ends of the beam were pin connected and the ends near the column were modelled with SOLID43 element to represent beam end connector (Fig. 9). The material model was elastic–plastic with strain hardening capabilities and having the properties shown in Table 1. The material properties were

<table>
<thead>
<tr>
<th>( \sigma_y ) (MPa)</th>
<th>( \sigma_u ) (MPa)</th>
<th>( E ) (GPa)</th>
<th>( E_{st} ) (MPa)</th>
<th>( \epsilon_u ) (%)</th>
<th>Elong. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>365</td>
<td>569</td>
<td>212</td>
<td>3444</td>
<td>1.95</td>
<td>29</td>
</tr>
</tbody>
</table>

The material properties used in FEA.

<table>
<thead>
<tr>
<th>Element name</th>
<th>SHELL63</th>
<th>SOLID45</th>
<th>CONTA173</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position of connector element</td>
<td>Upright</td>
<td>Connector hook</td>
<td>Contact between connector and upright</td>
</tr>
<tr>
<td>Description</td>
<td>Plastic shell element</td>
<td>3D structural solid element</td>
<td>3D surface-to-surface contact element</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>( x, y, ) and ( z ) translational and rotational displacements</td>
<td>( x, y, ) and ( z ) translational displacements</td>
<td>( x, y, ) and ( z ) translational displacements, temperature</td>
</tr>
</tbody>
</table>
obtained as per BS 5950 [5] after taking sample coupons from the sections tested. Properties of various finite elements used for the analysis are given in Table 2. The entire assembly along with meshing is shown in Fig. 9. Load is gradually applied on top of the column section in steps, and the corresponding rotations of the connector were monitored using four nodes as shown in Fig. 10. The deformed shape during the finite element analysis with Von Mises stress is shown in Fig. 11.

5.3. Frame test

Finite element analysis of the full scale frame test done was carried out incorporating the flexibility values obtained by single and double cantilever tests using COMBIN39 element available in ANSYS [1]. For flexible connection an element of zero length is introduced between beam-column connections as shown in Fig. 13. COMBIN39 is added here as flexible connector. Moment vs. rotation values obtained from the cantilever and double cantilever test are given as real constants for this element. For the column BEAM24 element, which is a 3D thin-walled beam element is used. BEAM4 and LINK8 elements are used for beam and bracings, respectively. The properties of various finite elements used are given in Table 3.

6. Comparison of experimental and FEA results

As seen from Fig. 8, difference in experimental and FEA during initial stages is due to slackness in the connector, once the connector is settled in the column slot, both test and FEA results are found to match well. However, the finite element model was not able to capture the failure mode which was observed in the test. The dead-end failure took place with tearing of the column perforation by the hook. The beam to column connection stiffness obtained from the finite element analysis cantilever test also agrees well with the test results. However, the finite element model was not able to capture the failure mode which was observed in the test. In the test the failure took place with tearing of the column perforation by the hook.

Fig. 12 gives the comparison between double cantilever test and FEA. The test and FEA results are found to match well after settling of the connector in the column slot. Here, the
Fig. 8. Comparison between experiment and finite element analysis (single cantilever test).

Fig. 9. Finite element model of double cantilever test.

Fig. 10. Four nodes monitored to determine the rotation (double cantilever test).
failure was due to opening up of the column flanges during the test due to excessive axial pull.

Load vs. strain graphs of the full scale frame test shown in Figs. 14 and 15 confirm that the test was carried out within the elastic limits, since both loading and unloading paths remaining the same. The moment vs. rotation values obtained from both single and double cantilever tests were used as the flexibility values for the COMBIN39 element during the frame analysis using ANSYS [1]. Table 4 gives the comparison of bending moment and deflection.

Fig. 11. Finite element simulation Von Mises stress (double cantilever test).

Fig. 12. Comparison between experiment and finite element analysis (double cantilever test).

Fig. 13. Frame with flexible joints.
7. Conclusions

A conventional single cantilever test and a newly proposed double cantilever test were conducted to determine the flexibility of beam-column connectors. The experimental results were compared with non-linear finite element analysis. The results of the double cantilever test closely matched with the finite element analysis. In the double cantilever test, the connector is subjected to three types of forces namely moment, shear and axial pull thus representing the exact field conditions.
The shear to moment ratio in an actual frame is better represented by this double cantilever test. This was further confirmed with the full scale frame test along with finite element analysis of the same (see Table 4). Therefore, to determine flexibility of the connector the double cantilever test can be used in lieu of conventional cantilever test. The double cantilever test has been found to be far superior to conventional single cantilever test.

**Table 4**
Comparison of BM and deflection between ANSYS and full scale test

<table>
<thead>
<tr>
<th>Description</th>
<th>ANSYS model stiffness from</th>
<th>Full scale test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single cantilever test</td>
<td>Double cantilever test</td>
</tr>
<tr>
<td>BM at center of span (kN-m)</td>
<td>2.086</td>
<td>2.03</td>
</tr>
<tr>
<td>Deflection at center of span (mm)</td>
<td>3.80</td>
<td>3.679</td>
</tr>
</tbody>
</table>

The shear to moment ratio in an actual frame is better represented by this double cantilever test. This was further confirmed with the full scale frame test along with finite element analysis of the same (see Table 4). Therefore, to determine flexibility of the connector the double cantilever test can be used in lieu of conventional cantilever test. The double cantilever test has been found to be far superior to conventional single cantilever test.

**References**