Angle Cleat Base Connections

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Abstract

Tests, performed on base connections fabricated from cold-formed channels and hot-rolled angle cleats, are presented in this paper. This research is part of an on-going research to develop portal frames made out of cold-formed steel. The base connections are subjected to an axial load and moment. Hot-rolled angle cleats are used to prevent premature failing of the base connections. Several loading configurations are considered and these are dependent on the eccentricity of the load. In all the tests the cold-formed channels failed by local buckling. A significant amount of bearing distortion was observed in the heavily loaded flange. The use of bolted angle cleats allows for a simple connection to be developed, which can result in significant cost savings within the steel construction industry.

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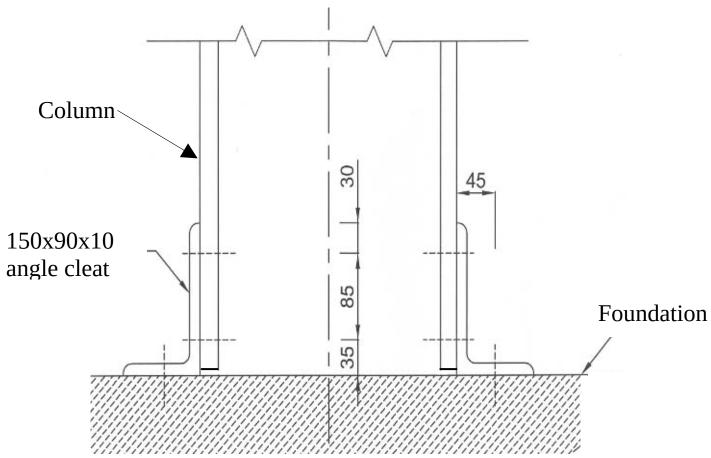
Introduction

The weight of a steel structure including all other loads (live loads or dead loads) to which it may be subjected are borne by its column base which transmit these loads to the foundation. The successful transfer of these loads to the foundations requires that the base connections be properly designed and installed, because this is critical for the effective and efficient performance of the structure. A key factor in erecting a building is the simplicity in which the base connections can be produced. The design and detailing of the connections in a building has a significant effect on costs.

Welded base plate connections are commonly used within the construction industry to connect the column to the base plate. This type of connection can create assembly problems and uncertainties, in terms of workmanship and economy. A viable alternative to this connection, especially for portal frames spanning from 5 to 16m, are angle cleats base connections. The main advantage of angle cleat connections is that no welding is required, thus they can fabricated and assembled with minimum skill. The aim of this investigation is to determine the feasibility of using angle cleat connections as column base connections. The results obtained from the experiments are then compared with the ones determined from the theoretical analysis to evaluate whether the connection is sufficient in resisting these loads.

Structural form of the connections

In previous work, portal frames were developed from cold-formed lipped channels, connected back-to-back at the eaves and apex connections (Dundu and Kemp 2006). Current investigations are focused on the base connections of these frames. Three base connections are investigated in these tests; 1) Base connections with cold-formed angle cleats, connected to the flanges only, 2) Base connections with hot-rolled angle cleats, connected to the flange only and 3) Base connections with hot-rolled angle cleats connected on both the flanges and web. In base connections 1 and 2, angle cleats are connected to the flanges by two bolts and a single bolt secures them to the foundation as shown in Figure 1(a). Since the connection configuration in this figure is such that loads are transferred from the entire column section through the flanges only to the angle cleats, in order to increase the capacity of the connection it was decided to incorporate another angle cleat in the web to form base connection 3. The plan of this connection is shown in Figure 1(b). In both base connections the angle cleats are of the same size and the column is short in order to prevent premature failure caused by overall flexural buckling. The angle cleats are connected to the column such that no end bearing at the bottom of the column takes place; instead the load is fully transferred to the foundation through angle cleats. As shown in the figure, the longer leg of the cleats is connected to the flange of the column. The angle cleats were chosen so that they can accommodate two bolts.



(a) Base connection 1 and 2

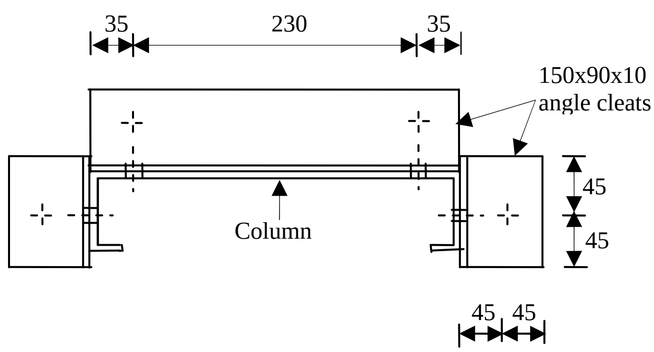


Figure (b) Plan of base connection 3

Figure 1 Base connections

Test procedure of base connections

Prior to testing the base connections, material properties had to be determined. Coupon tests were prepared to establish the yield stress, ultimate stress and the elastic modulus of the channel sections. The yield stress and the elastic modulus are used to calculate the effective area of the channels and the squash load of the channels, whilst the ultimate stress is used to calculate the bearing resistance of the connections (see Tables 2). No material tests were carried out for the bolts and the hot-rolled angle cleat since their strength was found to be less critical than the strength of the channels. Grade 8.8 bolts have a minimum tensile stress of f_u = 800MPa (SASCH, 2005). Standard washers were placed under the head of the M20 bolts and under the nuts to guard against rotation of the bolt and deformation of the thin material adjacent to the bolt. The diameter of all bolt-holes was made 1mm greater than the nominal diameter of the bolt to reduce slip in the connections. All bolts were fully threaded.

The bases were loaded using a 500kN Instron Testing Machine. A total of 24 column bases were tested. For each base connection, two tests were performed with the load applied at centroid of the column section (Load case 1) as shown in Figure 2(a), one third of the depth of the section (Load case 2), edge of the column section (Load case 3) and through a beam (Load case 4) as shown in Figure 2(b). A beam was introduced in Load case 4 in order to generate a large moment into the connection. Variables in the tests include the size of the column sections, number and type of angle cleats, material properties, and location of loading. A list of these variables and the corresponding bases are given in Table 1. High strength structural bolts, size M20, of Grade 8.8 steel are used for the base connections.

(a) Load cases 1-3

(b) Load case 4

Figure 2 Base connections with angle cleats connected to the flange only

Table 1 Variables in the test set-up

Angle cleats	Load Cases	Column Section	f_y (MPa)	f_u (MPa)
Cold-formed angle cleats connected to the flange only				
150x75x3	Load Case 1	300x50x20x3	262.43	345.80
150x75x3	Load Case 2	300x50x20x3	262.43	345.80
150x75x3	Load Case 3	300x50x20x3	262.43	345.80
*150x75x3	Load Case 4	300x65x20x3	256.00	315.00
Hot-rolled angle cleats connected to the flange only				
150x90x10	Load Case 1	300x65x20x3	346.05	473.90
150x90x10	Load Case 2	300x65x20x3	346.05	473.90
150x90x10	Load Case 3	300x65x20x3	346.05	473.90
*150x90x10	Load Case 4	300x65x20x3	256.00	315.00
Hot-rolled angle cleats connected to the flange and web				
150x90x10	Load Case 1	300x75x20x3	264.72	365.88
150x90x10	Load Case 2	300x75x20x3	264.72	365.88
150x90x10	Load Case 3	300x75x20x3	264.72	365.88
150x90x10	Load Case 4	300x75x20x3	264.72	365.88

* Note the change in material properties

All tests are arranged in such a way that the column does not bear on its bottom face, but is suspended entirely by M20 bolts. Since these tests were performed in the laboratory the angle cleats were bolted to a plate instead of the concrete foundation. A compressive loading was applied along the minor axis of the channel sections through specially designed plates with circular grooves at the centre to accommodate a steel ball. The steel ball ensured that the applied load is a point load and the bottom plate prevented the top of the stub column from localized damage. The applied load and shortening were recorded at pre-determined intervals using an automatic data acquisition system as the experiments were carried out. The load was applied at a gradual rate of 2mm/min to allow the structure to deform in a ductile manner. In Load Case 4, the load was applied at the shear centre of the column section to prevent it from twisting.

Modes of failure

Cold-formed angle cleat connected to the flanges only

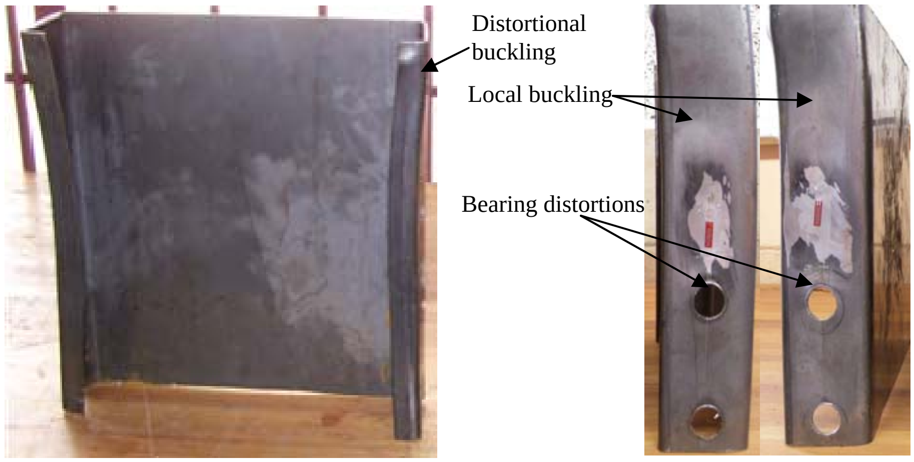
In all tests where cold-formed angle cleats were used the base connection failed prematurely by the deformation of the angle cleats. When the load was gradually applied at the centroid of the column section, the first sign of deformation was observed at the bottom of the web as it curved into a parabolic shape (Figure 3(a)). This was followed by the deformation of the angle cleats. The deformation of the angle cleats became excessive as the load was increased, consequently causing the set-up to fail. Significant cross bending occurred in the channel (Figure 3(b)) when the load was applied at the edge of the column section (Load case 3). This was immediately followed by the deformation of the angle cleat, directly below the load. The set-up ultimately failed due to excessive deformation of this angle cleat. No deformation was experienced in the other angle cleat, implying that little or no load was carried by this angle cleat. In the case where the load was applied through a beam the moment uplifted one angle cleat and a compressed the other. The base connection failed by the opening up of the angle cleat on the tension side and the closing of the angle cleat on the compression side. No bearing distortions were experienced in the bolt holes of all tests in this group.

(a) Deformation of web and angle cleats (b) Cross-bending of channels

Figure 3 Failure of cold-formed angle cleats connected to the flange only

Hot-rolled angle cleats connected to the flanges only

Distortional buckling of the stub column was experienced in all the tests conducted. In Load Case 1, where the compressive load was applied at the centre, distortional buckling resulted in equal outward movement of the column flanges as shown in Figure 4 (a). Large deformations occurred in both flanges of the column just above the angle cleat. In the other two cases distortional buckling was more pronounced in the flange subjected to a larger force. The final mode of failure in all tests where rigid cleats were used was local buckling in the flange (see Figure 4(b)). Local buckling occurred after considerable rotation of the flange above the angle cleat. After local buckling, the applied load dropped slowly.



(a) Distortional buckling (b) Buckling and bearing failure

Figiure 4 Filure of hot-rplled angle cleats connected to the flange only

After testing, it was observed that both channels experienced significant bolt-bearing deformations around the bolt-holes. These bearing deformations or distortions were found to be of equal magnitude in the first series of tests, where the compressive load was applied at the centre. In the other two cases, where the load was applied eccentrically from the centre, no bearing deformation was observed in the lightly loaded flange. Bearing distortions were more pronounced in the flange that transferred more load to the angle cleat (Figure 4(b)). Bearing distortion of steel around bolt-holes is a ductile mode of failure and provides the ductility required for moment redistribution.

Hot-rolled angle cleats connected to the flanges and web

As in hot-rolled angle cleats connected to the flange only, three modes of failure were identified in these base connections, that is, distortional buckling, local buckling of the channel section and bearing failure around the bolt-holes. Distortional buckling was observed in load cases 1-3. Local buckling of the channel section was the final mode of failure in all load cases. Deformation began in the flange as a result of distortional buckling and progressed into the web. Unlike base connections of hot-rolled angle cleats connected in the flange only, where local buckling occurred just above the cleats, in this case local buckling was experienced at the beam-column connection. This mode of failure did not occur close to angle cleats because the base was significantly stiffened. Bearing distortion was more visible in specimens where the load was applied away from the column centre (load case 2, 3 and 4). .

(a) Local buckling due to Load case 1 (b) Local bucking due to Load Case 4

Figure 5 Failure of hot-rolled angle cleats connected to the flange and web

Test Results

A summary of the average maximum load and moment, applied on the base connections and the calculated unfactored resistances are given in Table 2. In this table, N_{max} and M_{max} are the maximum vertical force and moment applied to the base, respectively, N_y is the squash load ($A_{ef}f_y$) of the column and V_{rj} is the resistance of two bolts. The area (A_{ef}) is calculated based on the effective properties of the sections. The joint resistance V_{rj} is evaluated based on the bearing resistance of the plate, which in all cases is much less than the shearing resistance of the bolts. Based on the design recommendation of Kemp (2001), a coefficient C of 1.8 for a standard washer under the nut and bolt head is used in the bearing resistance calculations. This factor depends on the ratio of bolt diameter to member thickness. Bearing resistance or capacity (B_r) of the connections is established from the following equation.

$$B_r = atf_u \leq Cdtf_u \quad (1)$$

where, t is the thickness of channel, d is the diameter of bolt, f_u is the minimum tensile strength of the channel, a is the distance from centre of hole to the edge towards which the force is directed and C is the bearing coefficient. It is assumed that the force applied to the bolts in the flanges is shared equally between the two bolts. These resistance values are determined using the South African code, SANS 10162-2-2005. This code is based on the Canadian structural steel code, CAN-S16.1-M89.

Table 2 Comparison of calculated and tests results

Load Cases	Column Section	N_{max} (kN)	M (kNm)	Load on Angle Cleats (kN)		N_y (kN)	Vrj (kN)
				LHAC	RHAC		
Cold-formed angle cleats connected to the flange only							
1	300x50x20x3	79.06	0	39.53	39.53	213.27	74.69
2	300x50x20x3	57.79	2.89	19.26	38.53	213.27	74.69
3	300x50x20x3	37.63	5.64	0	37.63	213.27	74.69
4	300x75x20x3	16.00	8.00	0	16.00	247.60	68.04
Hot-rolled angle cleats connected to the flange only							
1	300x65x20x3	200.00	0	100.00	100.00	282.73	102.36
2	300x65x20x3	150.00	7.50	50.00	100.00	282.73	102.36
3	300x65x20x3	110.00	16.50	0	110.00	282.73	102.36
4	300x75x20x3	43.67	22.33	0	43.67	247.60	68.04
Hot-rolled angle cleats connected to the flange and web							
1	300x75x20x3	201.23	0	100.62	100.62	254.41	79.03
2	300x75x20x3	159.76	8.00	53.25	106.51	254.41	79.03
3	300x75x20x3	85.28	12.79	0	85.28	254.41	79.03
3	300x75x20x3	36.98	21.27	0	36.98	254.41	79.03

A comparison of the test results and calculated unfactored yield resistance shows the applied load for each case to be smaller than the unfactored yield resistance (N_y). The maximum vertical force of Load Cases 1, 2, 3 and 4 for the base connection with cold-formed angle cleats connected in the flange only, achieved 37%, 27%, 18% and 6% of the squash load, respectively. These low forces were caused by the premature failure of the cold-formed angle cleats. Significant increases in load is realised when hot-rolled angle cleats are used, instead of the cold-formed angle cleats. However, the yield resistance of the channel is not attained due to local buckling failure. Load Cases 1, 2, 3 and 4 achieved 71%, 53, 39% and 18% of the yield resistance when the hot-rolled angle cleats are connected to the flange only. Local buckling was initiated in the flanges followed by the buckling of the web. In order to make the base connection stiffer than the one with hot-rolled angle cleats in the flange only, another angle cleat was connected to the web in the last configuration. As indicated in Table 2, this configuration did not achieve the desired results. There is little or no increase in base connection resistance, compared to the base connection with hot-rolled angle cleats connected to the flange only. This can be explained by the fact the base connection did not fail, instead the base resistance is determined by the strength of the column section.

In the base configurations with the angle cleats connected to the flanges only and the load is applied at the centre, the stress from the column to the bolts is transferred at approximately 45°. Half of this load is resisted by the Right Hand Angle Cleat (RHAC) and the other half is resisted by the Left Hand Angle Cleat (LHAC). In Load Case 2 of the same base configuration, the load is applied at one third of the depth of the channel. Consequently, there is a proportional distribution of the force from the column, with two-thirds of the force carried by the Right Hand Angle Cleat and the other one-third carried by the Left Hand Angle Cleat. Obviously this means that one column flange is more stressed than the other. In Load case 3, where the load is applied at the edge of the channel, the stresses are mainly concentrated in the corresponding angle cleat connection. The other base connection carries very little or no force at all. All load cases failed when the heavier loaded flange achieved a force of about 38kN for the cold-formed angle cleats and 100kN for the hot-rolled angle cleats. The bolts connecting the column to the angle cleat did not fail. Bolt-bearing distortions around bolt-holes (not complete failure) were only observed around holes. This means that the capacity of the bolts in shear and bearing was not reached despite the fact that partial bearing failure occurred in the connection.

Load-displacement graphs

The behaviour of the three base connections are shown by load-deformation curves in Figures 6, 7 and 8. These load-displacement curves represent the average curve for the tests in each load case. The load-deflection curves for Load Case 4 are deliberately excluded from these graphs because the base connections experienced relatively large deflections and low loads in comparison with other load cases. The load-deflection curves show the initial stages to be linear followed by a non-linear range. The non-linear response and decreasing connection stiffness exhibited late in the loading sequence is attributed, primarily, to local buckling in the flange. The non-linear response exhibited by the structures occurs at approximately 85% of the ultimate load. After this point large deformations take place and result in the collapse of the base. Both graphs show decrease in load carrying capacity of the base connections as the eccentricity of the applied load was increased.

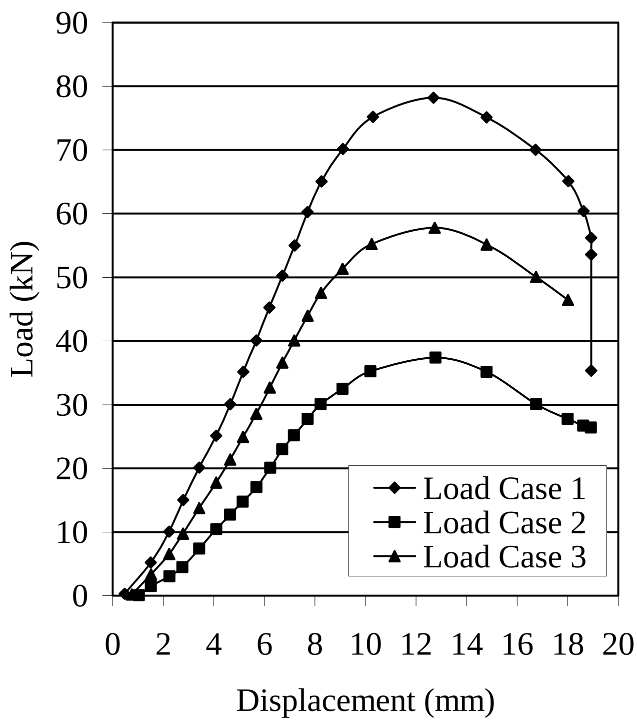


Figure 6 Cold-formed angle cleats, connected to the flanges

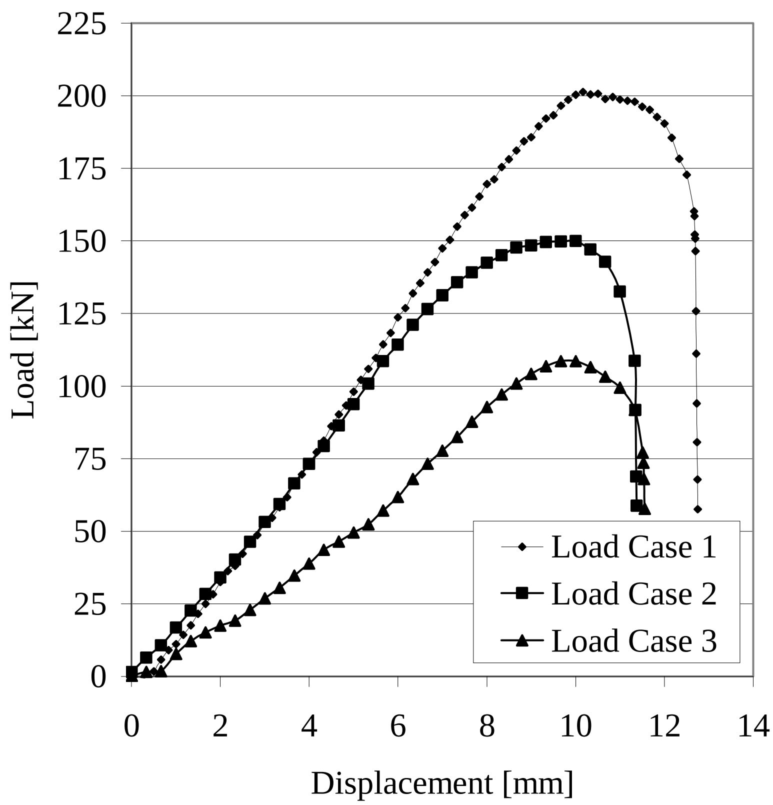
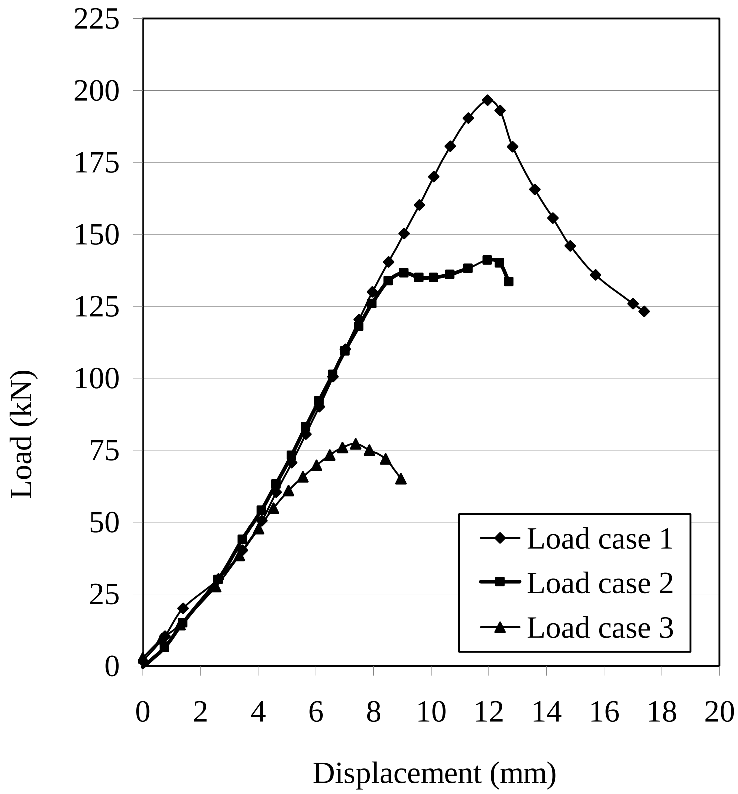


Figure 7 Hot-rolled angle cleats, connected to the flange only



Figiure 8 Hot-rolled angle cleats connected on both the flanges and web

Conclusions

This paper shows that angle cleat base connections can be a viable alternative to welded base connections, especially for cold-formed portal frames spanning from 5 to 16m. Observed modes of failure include premature deformation of the angle cleats, distortional and local buckling of the channel section and bearing distortion in the bolts. Premature deformation of the angle cleats was experienced in all tests where cold-formed angle cleats were used, whilst distortional buckling, local buckling and bearing failure were experienced in connections with hot-rolled angle cleats. The final mode of failure of base connections with hot-rolled angle cleats was local buckling of the flange followed by the web. Local buckling was made more critical by stress concentrations in the bolted flange. The non-linear load-shortening response exhibited late in the loading sequence of all the load cases is attributed, primarily, to ductile bolt-bearing deformation and local yielding of the flange below the inside bolt. Bearing distortion of bolt-holes is important in that it provides the ductility required for moment redistribution.

Acknowledgements

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